U.S. 101 MP 102.97 Unnamed Tributary to Big Creek (WDFW ID 990033): Preliminary Hydraulic Design Report

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1 Introduction

To comply with United States et al. vs. Washington et al. No. C70-9213 Subproceeding No. 01-1 dated March 29, 2013 (a federal permanent injunction requiring the State of Washington to correct fish barriers in Water Resource Inventory Areas [WRIAs] 1–23), the Washington State Department of Transportation (WSDOT) is proposing a project to provide fish passage at the United States Highway 101 (U.S. 101) crossing of an unnamed tributary (UNT) to Big Creek at Mile Post (MP) 102.97. This existing structure on U.S. 101 has been identified as a fish barrier by the Washington Department of Fish and Wildlife (WDFW) and WSDOT Environmental Services Office (ESO) (site identifier [ID] 990033) and has an undetermined length of habitat gain.

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Per the injunction, and in order of preference, fish passage should be achieved by (1) avoiding the necessity for the roadway to cross the stream, (2) use of a full-span bridge, or (3) use of the stream simulation methodology. The crossing was evaluated using the unconfined bridge design methodology because the floodplain utilization ratio is greater than 3, and incorporated aspects involving the stream simulation design methodology.

The crossing is located in Grays Harbor County 6.4 miles southeast of Humptulips, Washington, in WRIA 22. The highway runs in a north–south direction at this location and is about 1,700 feet (ft) from the confluence with Big Creek. The unnamed tributary generally flows from north to south beginning approximately 8,000 feet upstream of the U.S. 101 crossing (Figure 1).

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The proposed project will replace the existing 43-inch (in) (rise) by 73-inch (span), corrugated metal pipe arch, measuring 96 feet in length, with a structure designed to accommodate a minimum hydraulic opening of 24 feet. A specific structure type will be determined by others during future phases of the design. The proposed structure is designed to meet the requirements of the federal injunction using the unconfined bridge design criteria as described in the 2013 WDFW *Water Crossing Design Guidelines* (WCDG) (Barnard et al. 2013). This design also follows the WSDOT *Hydraulics Manual* (WSDOT 2019) with supplemental analyses as noted.

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A draft Preliminary Hydraulic Design (PHD) report was prepared in 2020 by WSDOT and HDR Engineering, Inc. under Agreement Number Y-12374 between HDR and WSDOT Environmental Services Office. WSDOT received review comments on the draft PHD report from WDFW and the Quinault Indian Nation (QIN). As part of Kiewit's Coastal-29 Team of the US 101/SR 109 Grays Harbor/Jefferson/Clallam, Remove Fish Barriers Project under a Progressive Design-Build (PDB) contract between Kiewit and WSDOT, Kleinschmidt Associates (KA) reviewed the draft PHD report, updated the hydraulic modeling and design, addressed WDFW and Tribe comments, and prepared this Draft Final PHD report using material in the draft PHD report as a starting point. Responses to WDFW and Tribe comments are included in Appendix J. While HDR's original field observations and measurements, and selected figures have been retained in this report, all writing and analyses in the draft PHD report have been reviewed, edited, and updated where determined necessary.

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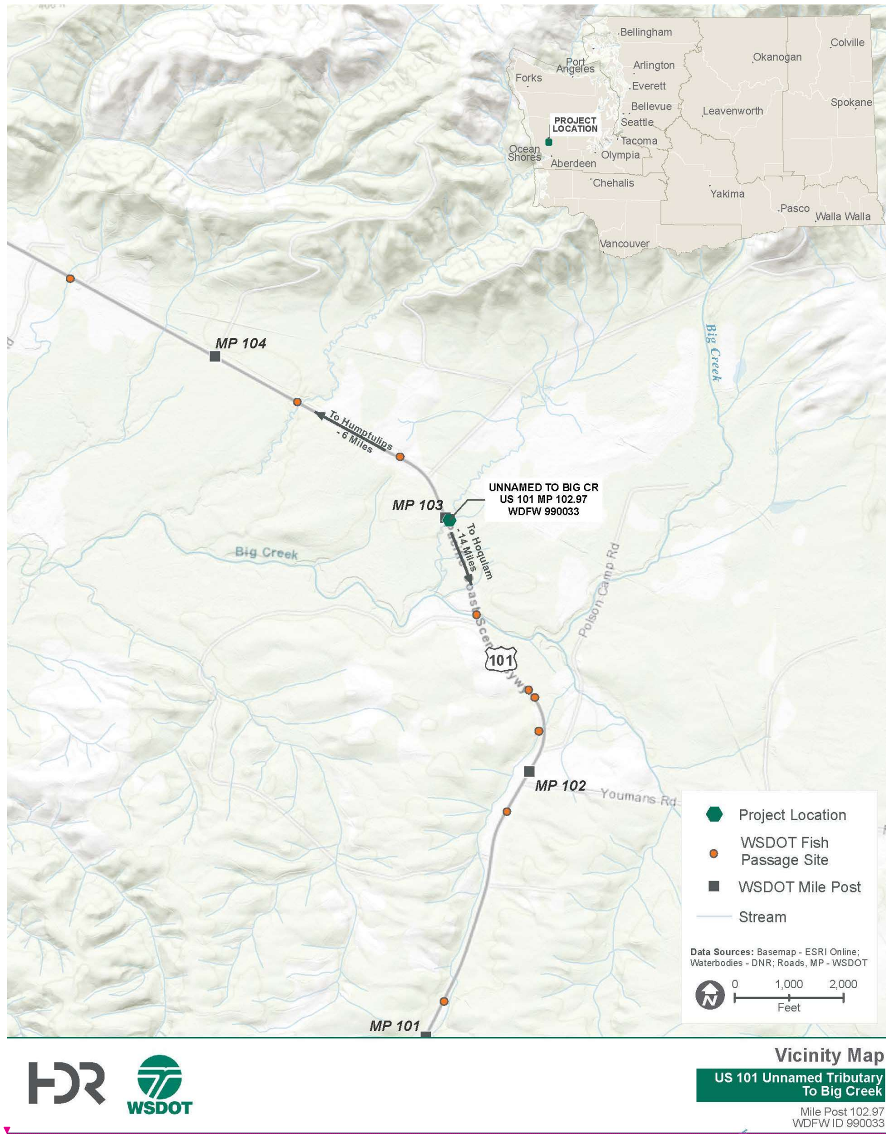

Figure 1: Vicinity map

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2 Watershed and Site Assessment

The existing site was assessed in terms of watershed, land cover, geology, floodplains, fish presence, observations, wildlife, and geomorphology. This was performed using desktop research including aerial photos; resources such as the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), and WDFW; past records like observation and fish passage evaluation; and site visits.

2.1 Watershed and Land Cover

The project stream flows in a generally southwesterly direction and joins Big Creek approximately 1,700 feet downstream of the U.S. 101 culvert crossing. Big Creek drains into the Humptulips River, which flows southerly to Grays Harbor and eventually into the Pacific Ocean. The watershed is generally forested, with drainage intercepted and routed under the U.S. 101 crossing and a network of forest roads. According to StreamStats, the basin has a mean slope of 11.2 percent, with a total basin relief of 458 feet and less than 1 percent of slopes greater than 30 percent (USGS 2016). The 2016 National Land Cover Database (NLCD) map (Figure 2) shows land cover at that time to consist primarily of evergreen forest and scrub/shrub (NLCD.

). The Grays Harbor County Assessor's Office web mapping database indicates the stream flows through various parcels owned by timber companies and small forest landowners. Timber harvest has occurred as a patchwork of clearcuts across the basin over time. Prior to 2005 and the implementation of Washington's Forest Practices Habitat Conservation Plan, timber harvest occurred without leaving a riparian management zone, including on the parcel on the downstream side of the project culvert (Figure 3).

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Table 1: Recent major land over composition upstream of culvert

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Land cover class	Basin coverage (percent)
Evergreen forest	65.1
Scrub/shrub	25.6
Developed, open space	5.2
Woody wetlands	2.5
Developed	0.9
Mixed forest	0.7

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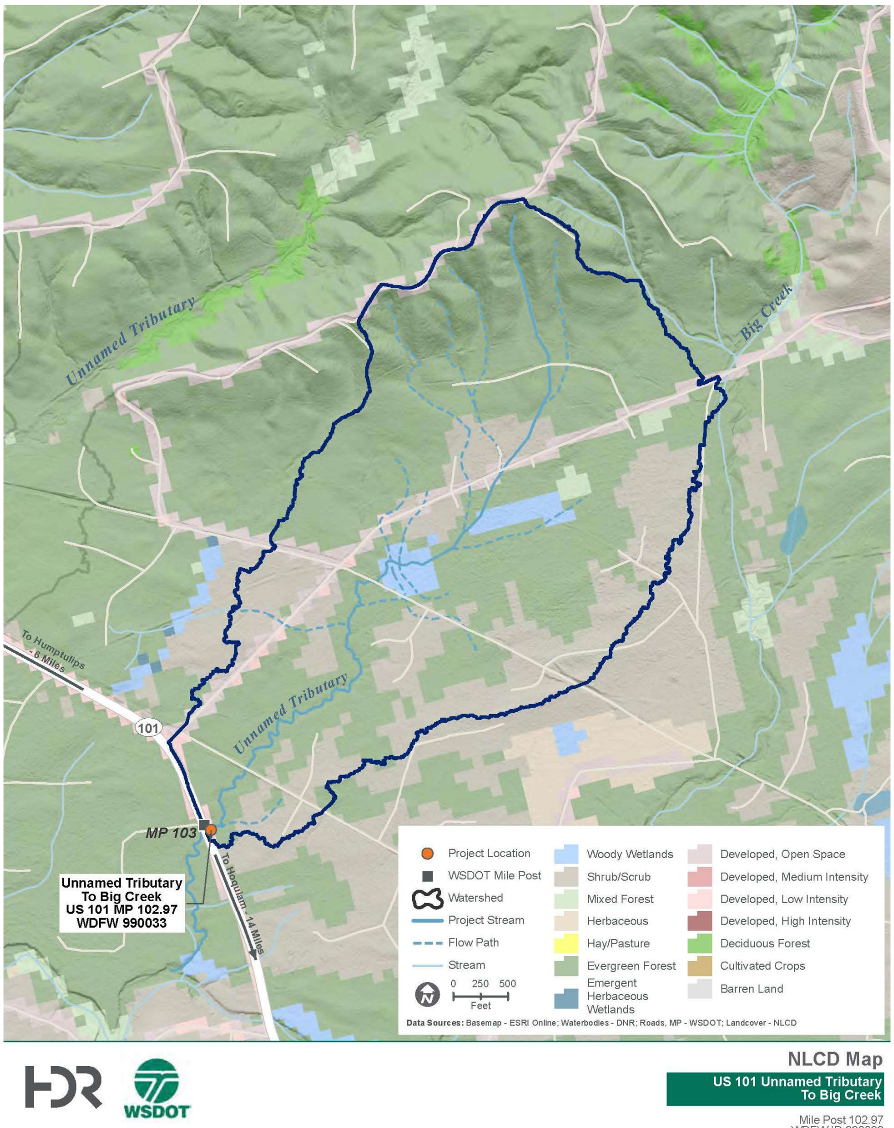

Figure 2: Land cover map (NLCD 2016). Approximate catchment area upstream of the culvert is depicted

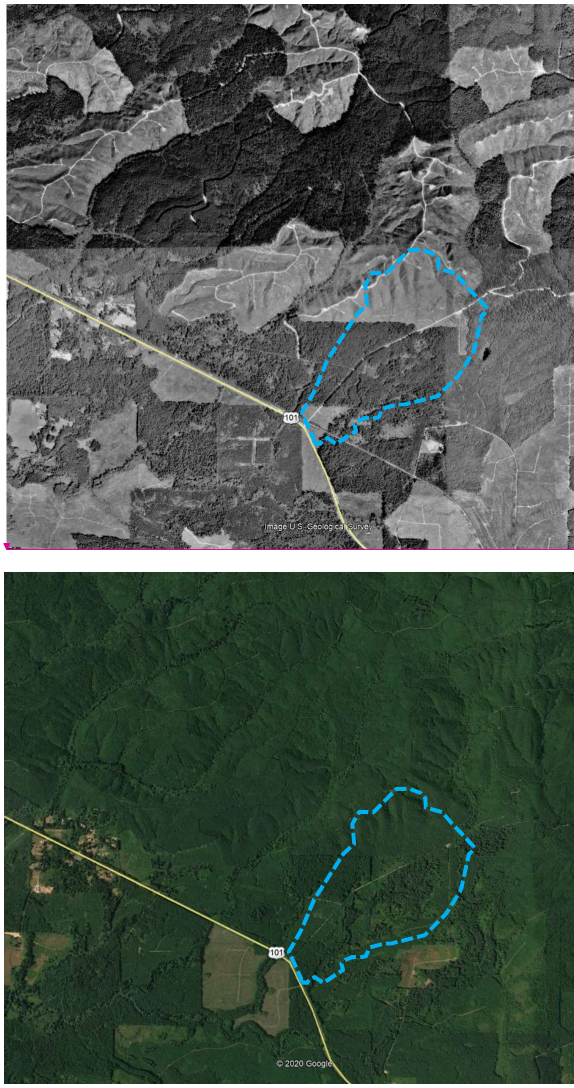

Figure 3: Aerial photographs of the project basin taken in 1990 (top) and 2018 (bottom), showing extents of timber harvest activity. Approximate catchment area upstream of the culvert is depicted

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2.2 Geology and Soils

The region is a tectonically active area with mapped quaternary faults and active subduction plate boundary causing uplift. The surficial geologic for the basin was mapped at a 1:100,00 scale (Logan 2003) and obtained from the Washington State Department of Natural Resources (WDNR) Geologic Information Portal (Washington Division of Geology and Earth Resources, 2016). The upper reach of the basin consists of uplifted Humptulips Formation, (Em(2ht)) which consists of Eocene-age marine sedimentary rocks (Figure 4). In contrast, the bottom three-quarters of the watershed lies in Pleistocene alpine glacial outwash (Qapo) that occupies a structural trough. The Pleistocene Age, alpine glacial outwash includes silt, sand, and gravel that is commonly iron-oxide stained that was deposited in streambeds and fans. It may form low terrace surface, which are commonly dissected (Logan, 2003). No detailed geological maps have been published and Logan's mapping was completed before the availability of LiDAR data.

Using a LiDAR DEM viewed at 1:4000 scale, it is evident that throughout the post-glacial period, the UNT has reworked and downcut through the outwash in an attempt to equilibrate to the baselevel elevation set by Big Creek. Convexity in the bottom portion of profile (see section 2.8.4) suggests the stream has not fully equilibrated to the dropping base level set by Holocene incision of Big Creek (Figure 5).

Soils in the watershed are composed primarily of Hoquiam silt loam, with smaller pockets of Nemah silty clay loam and Zenker silt loam in the upper basin (NRCS, 2020). No landslide hazards were identified in the Geologic Information Portal within the project basin (Washington Geological Survey, 2020a, and 2020b).

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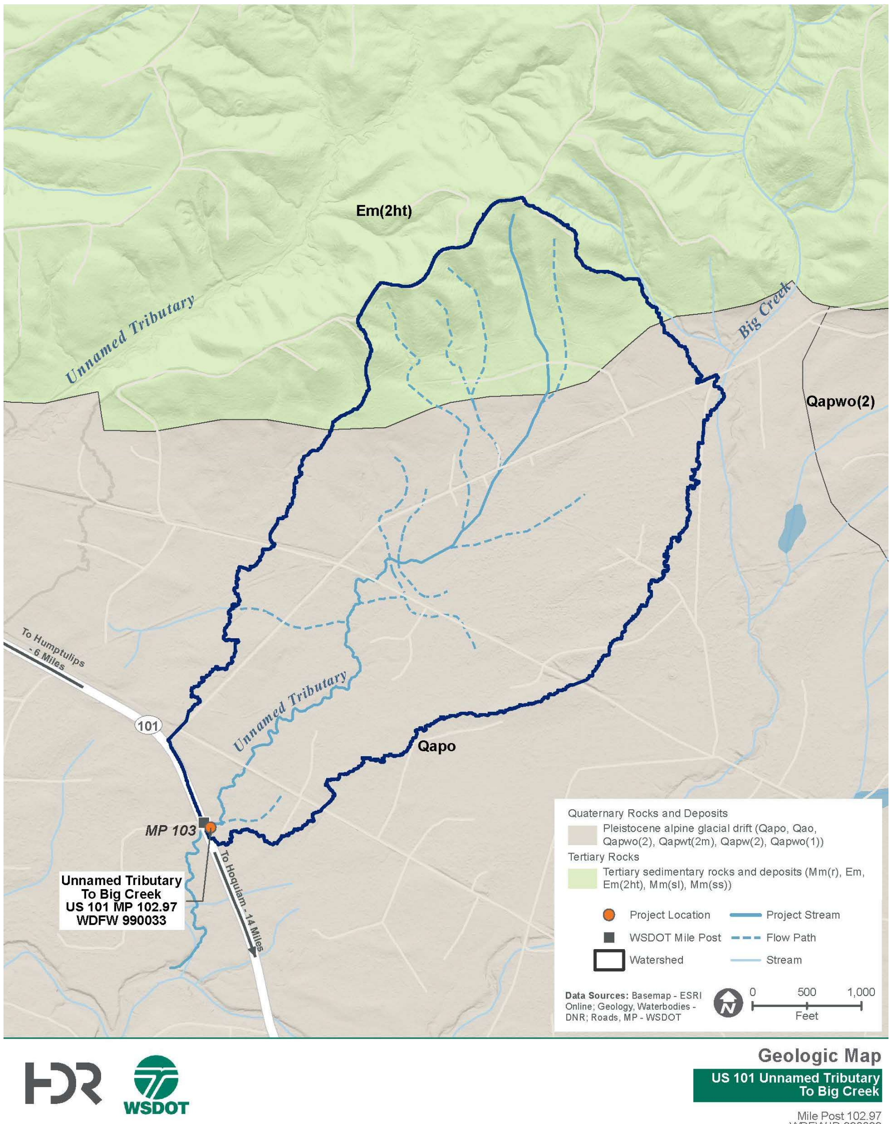

Figure 4: Geologic map. Approximate catchment area upstream of culvert is depicted.

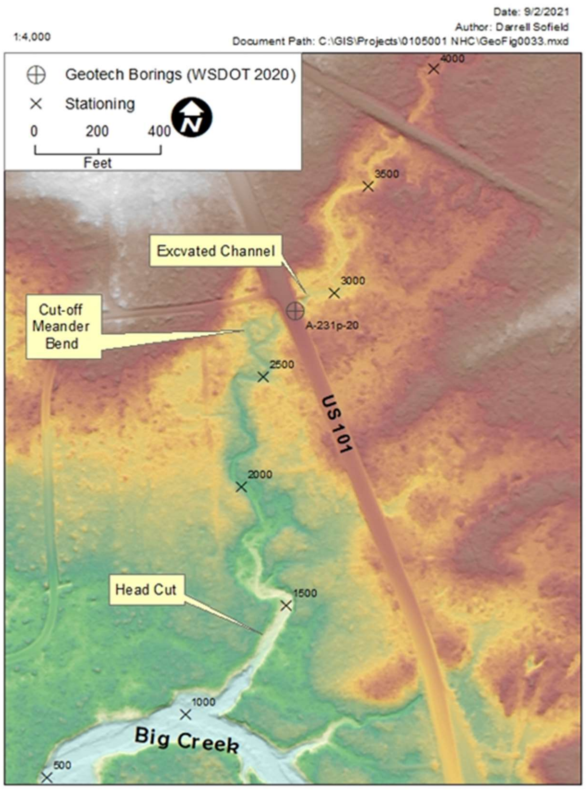

Figure 5: Additional geologic features discernable on LiDAR Digital Elevation Model (DEM)

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2.3 Floodplains

The crossing is not within a regulatory Special Flood Hazard Area, which is the 1 percent or greater annual chance of flooding in any given year. The project site crossing is located in Zone X (unshaded) based on FEMA Flood Insurance Rate Map (FIRM) 53027C0470D effective February 3, 2017 (see Appendix A). An unshaded Zone X represents areas of minimal flood hazard from the principal source of flooding in the area (Big Creek) and is determined to be outside the 0.2 percent annual chance floodplain. The mapped regulatory floodplain for Big Creek begins approximately 1,600 feet downstream of the crossing.

2.4 Site Description

The project stream is a tributary to Big Creek, which then flows into the Humptulips River. The WDFW online fish passage database does not list any impassable barriers between the project culvert and the confluence of Big Creek, and a WDFW survey of the downstream reach did not find a barrier to anadromous fish access from the confluence with Big Creek (WDFW 2018). The existing culvert was documented by WDFW to have an estimated 67 percent passability as controlled by water depth in the culvert. The total length of habitat available upstream was undetermined in WDFW's (2021) barrier survey report. Habitat in the vicinity of the culvert appears to be primarily suitable for juvenile salmonids, and possibly adult resident salmonids.

2.5 Fish Presence in the Project Area

The online databases from WDFW and the Statewide Washington Integrated Fish Distribution (SWIFD) (2020) do not have data for this stream. Downstream, Big Creek is documented to have Coho Salmon (*Oncorhynchus kisutch*), Chum Salmon (*O. keta*), fall Chinook Salmon (*O. tshawytscha*), Steelhead (*O. mykiss*), and coastal Cutthroat Trout (*O. clarkii clarkii*) (SWIFD 2020, WDFW 2020a, StreamNet 2020). Steelhead that inhabit the watershed are part of the Southwest Washington distinct population segment (DPS) and are not currently listed under the Endangered Species Act (ESA).

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Coho Salmon appear to be the primary species living in the project stream (Table 2), and juveniles were recently observed upstream of the project culvert (WDFW 2021). Coastal Cutthroat Trout and resident rainbow/steelhead trout also potentially occur within the project reach (SWIFD 2020, WDFW 2020b). Small channel size and limited gravel quantities likely preclude adult salmon and Steelhead from using this stream for spawning. Rearing and overwintering juvenile Steelhead may potentially disperse upstream to reaches close to the project crossing. Other species spawning in Big Creek are less likely to be found in the project stream. For example, Chum Salmon juveniles do not tend to disperse upstream from spawning areas, and juveniles quickly move out to estuary habitat where most of their rearing occurs (Salo 1991). Bull trout presence is presumed in Big Creek but not in any nearby tributaries (SWIFD 2020, WDFW 2020a). Habitat in the UNT does not provide the cold, clear waters required by bull trout (Rieman and McIntyre 1993), and therefore they are not expected to be present.

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Table 2: Native fish species potentially present within the project area

Species	Presence (presumed, modeled, or documented)	Data source	ESA listing[a]
Coho salmon (*Oncorhynchus kisutch*)	Presumed (documented in Big Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Southwest Washington DPS[b] steelhead (*Oncorhynchus mykiss*)	Presumed (documented in Big Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Coastal cutthroat (*Oncorhynchus clarkii clarkii*)	Presumed (documented in Big Creek)	SWIFD 2020, WDFW 2020b	Not warranted

a. ESA = Endangered Species Act.

b. DPS = distinct population segment.

2.6 Wildlife Connectivity

The one-mile segment that the project reach falls in is ranked by WSDOT as 'High' priority for Ecological Stewardship and 'Low' priority for wildlife-related safety. Adjacent segments to the north/east and south/west ranked High for Ecological Stewardship and Low for Wildlife-related Safety. The final hydraulic design for this crossing will incorporate measures selected by WSDOT to provide habitat connectivity.

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2.7 Site Assessment

A site assessment was performed of fish habitat conditions, hydraulic and geomorphic characteristics, and the culvert based on field visits, WDFW's barrier inventory report (WDFW 2021), and a WSDOT survey. An initial visit occurred in 2020, with subsequent visits postponed until 2021 after the Covid-19 pandemic had begun to subside.

2.7.1 *Data Collection*

Site visits were performed on four occasions to collect data and observe conditions and characteristics influencing the hydraulic design:

- HDR visited the project site on May 14, 2020, to collect pertinent information to support development of an initial design, including bankfull width (BFW) measurements, and characterizations of instream fish habitat and floodplain conditions. Channel substrates, large wood accumulations and floodplain vegetation were characterized.
- Kleinschmidt-R2 and Kiewit visited the site on June 1, 2021 to corroborate the initial data collection findings, review the representativeness of the BFW and channel substrate measurements, and identify additional data collection needs.
- Kleinschmidt-R2 and Kiewit visited the site on June 15, 2021 to collect a bulk substrate sample, measure the hydraulic effect of natural downstream in-channel flow obstructions as it would affect hydraulic modeling predictions, and measure the typical size of mobile wood pieces upstream of the culvert as they would affect the determination of minimum freeboard requirements.
- Kleinschmidt-R2 and NHC visited the site on July 13, 2021 to support an evaluation of the long term vertical stability of the channel.

Field reports are presented for each visit in Appendix B. BFWs are summarized in Section 2.8.2.

WSDOT also surveyed the site in March 2020. The survey extended approximately 250 feet upstream of the crossing, 280 feet downstream of the crossing, and a total roadway survey length of 610 feet. The reach surveyed comprises the project reach within which most data were collected and observations made for use in developing the design. Survey information included break lines defining stream bank toes and tops and overbank areas along the channel. The data were used to generate hydraulic models and evaluate geomorphology during development of the hydraulic design.

2.7.2 *Existing Conditions*

2.7.2.1 Culvert

The existing structure is a 96-feet-long, approximately 43-inch-tall by 73-inch-wide corrugated metal pipe arch culvert with a gradient of approximately 0.1 percent. It is inferred from the surrounding topography that the original channel was straightened when the culvert was installed by shortcutting a relic channel meander (see Section 2.8.2). The inlet is situated below a hardpan grade control that forms a steep step below a much lower gradient segment of channel upstream (Figure 6). The outlet of the culvert is directed at a roughly 3 to 4 feet high vertical right bank (Figure 7), which curves sharply to the left within approximately 10 feet of the downstream end, indicating that high flow velocities exiting the culvert are insufficient to erode the underlying hardpan. This suggested low energy during flooding is consistent with observations of fine sediment accumulations above hardpan grade controls (see next section). There was some racking of debris at the downstream end of the culvert outlet scour pool.

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The culvert has not been identified as a chronic environmental deficiency or failing structure. WSDOT has not noted any maintenance problems.

Figure 6: Culvert inlet

Figure 7: Culvert outlet

2.7.2.2 Stream

The stream channel character differs upstream and downstream in the vicinity of the culvert. Upstream, the channel flows under a more open canopy through a wetland area with sections choked with dense growths of aquatic macrophytes and sedges (Figure 8). The downstream channel flows under dense growths of shrubs and trees, and flow is choked at several locations by racked-up accumulations of small woody debris and branches. The channel is narrower and more defined downstream of the culvert compared with sections upstream (Figure 9). There is a channel split downstream of the culvert associated with flow around a tree obstruction (Figure 10), and an embedded log across the bottom forming an approximately 6 inch drop in the right channel (Figure 11). Off-channel wetland channels/swales are also present.

The channel substrate consists of a series of hardpan grade controls with relatively thick, dense deposits of fine silt, sand, and organic material upstream of each control location, which is indicative of non-scouring velocities during flood events. Some gravel is present in the vicinity of the grade controls, including at the hydraulic control at the downstream end of a small scour hole below the culvert outlet. Banks are mostly low profile, soft/muddy, and densely vegetated. Small diameter trees are generally set back from the channel banks. The channel does not appear to be entrenched.

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The channel upstream and downstream of the culvert is variably blocked by large wood material (LWM) and racked up accumulations of woody and vegetative debris caught up on LWM and snags along the banks (Figure 12). There were three obstructions observed downstream of the culvert that are suspected to influence hydraulics at the road crossing, that block between approximately 25-35 percent of the bankfull flow area. At some locations logs span the channel (Figure 13), and elsewhere there are large stumps and logs partially or wholly submerged in the water (Figure 14).

2.7.2.3 Floodplain

The channel is generally unconfined upstream and downstream of the existing culvert, and flood flows readily engage overbank areas which are relatively flat with deadfall and other woody debris distributed randomly over the surface. The hydraulic modeling indicates the floodplain is activated at flows as low as the 2-year event both upstream and downstream (Appendix C). Evergreen trees were seen growing roughly 10 feet outside the channel. Riparian vegetation consists of ferns, shrubs, and trees 1 to 2 feet in diameter. Upstream of the culvert, the stream flows through a mixed forest consisting primarily of alder (*Alnus rubra*) and Douglas fir (*Pseudotsuga menziesii*). There is a dense shrub understory with native species including salmonberry (*Rubus spectabilis*) and willows (*Salix* spp.). The stream channel becomes less defined upstream, with heavily vegetated floodplains containing sedges, willows, and wetland vegetation including spirea (*Spiraea douglasii*). Downstream of the culvert, the stream flows through a mixed mature forest consisting primarily of Douglas fir, with some alder. A stand of even-aged Douglas fir formed the primary forest cover at the downstream end of the surveyed reach. There is a dense shrub understory throughout the reach with native species including salmonberry, willows, vine maple (*Acer circinatum*), sword fern (*Polystichum munitum*), and lady fern (*Athyrium filix-femina*). The mature forest and shrub cover provides good shading, nutrient inputs, and some potential for LWM recruitment.

Figure 8: View of wetlands floodplain at upstream end of surveyed reach

Figure 9: Typical view of channel downstream of culvert

Figure 10: Island with trees

Figure 11: Typical water surface drop across an embedded log

Figure 12: Racked debris

Figure 13: LWM across channel

Figure 14: LWM along channel banks

2.7.3 *Fish Habitat Character and Quality*

The mature forest and dense shrub, sedge, and grass cover provides shading, abundant nutrient inputs, and some potential for LWM recruitment. LWM is important in western Washington streams in that it provides cover for fish and contributes to stream complexity, which is beneficial to salmonids. There were 4 places noted during the first field visit where logs and woody material were present in the stream channel and banks, and a total of 16 key pieces of LWM was counted in the 250 feet long reach surveyed upstream of the culvert, ranging from 6 to 48 inches in diameter. Much of the LWM comprised several large conifer logs in the channel and banks, and a few downed trees lying across the channel, with branches and accumulated small woody debris among the floodplain vegetation. A log and rootwad form the left bank at the apex of the main bend in the reach and provide some instream habitat complexity. Some of the larger logs downstream of the heavily vegetated wetland areas provide good instream cover for fish.

The channel upstream of the culvert is slow flowing and consists of wide, shallow, vegetated areas at the upstream end, and a series of deep pools in the mid and downstream portions of the reach. The substrate consists almost entirely of fines and organic debris, with areas of aquatic vegetation. There is no suitable spawning habitat for any of the salmonid species that inhabit the stream in the surveyed reach. The pool habitat throughout the upstream reach provides good rearing habitat for the salmon species that inhabit the stream. Slow flowing pools and wetland areas make good off-channel rearing and overwintering habitat for juvenile coho and other salmonids, particularly when flows are high in the main rivers such as Big Creek.

Downstream of the culvert, logs and woody material were noted in the stream channel and banks at four locations. A total of nine key pieces of LWM was counted within the project reach surveyed by WSDOT, ranging from 5 to 18 inches in diameter. There was abundant small woody debris racked throughout the reach, but mainly near the upstream end and likely effecting backwater through the culvert during high flows. Much of the LWM in the reach is functioning in the stream channel and banks, providing some habitat complexity and cover for fish. The substrate in the downstream reach is composed almost entirely of fines, including areas of clay and hardpan, with a few areas of embedded gravel, and is generally unsuitable as spawning habitat for salmonid species. Most of the stream habitat consists of shallow runs and glides. Pool/riffle habitat is generally lacking except at the culvert outlet, where there is a channel-wide pool approximately 10 long and 2 feet deep with small woody debris racked at the tailout. There was also a small, shallow pool found at a bend under a larger channel spanning log near the downstream end of the surveyed reach.

2.8 Geomorphology

Geomorphic information provided for this site includes selection of reference reaches within the surveyed project area, the basic geometry and cross sections of the channel, stability of the channel both vertically and laterally, and various habitat features.

2.8.1 *Reference Reach Selection*

Two relatively straight sections of stream were chosen as reference reaches, situated approximately 70 feet upstream of the culvert (Reference Reach 1; Figure 15) and 250 feet downstream of the culvert (Reference Reach 2; Figure 16). They were considered representative of the different instream and floodplain hydraulic and geomorphic characteristics observed upstream and downstream of the culvert (Figure 17). The upstream reach is influenced hydraulically and geomorphically by a hardpan grade control upstream of the culvert, and by backwater from the culvert. The downstream reach is representative of natural conditions with abundant instream and floodplain roughness, and intermittent hardpan grade controls as well. Both reaches have an approximate average channel gradient of 0.7 percent. The reference reaches were relied on primarily for measuring bankfull dimensions for informing the design of the hydraulic opening width and the cross-section morphology of the constructed channel outside of the replacement structure footprint. The reference reach morphology was not used to design cross-section shape and planform underneath the replacement structure because vegetation controlling bank stability cannot generally grow there.

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2.8.2 *Channel Geometry*

Channel planform upstream of the crossing is characterized by a wider, meandering, and vegetated channel, and downstream the channel continues to meander but is narrower, and vegetation is mostly confined to the banks and floodplains. There is relic channel that splits to the north approximately 40 feet upstream of the existing culvert and is intersected by the road prism. The relic channel rejoins the current channel approximately 150 feet downstream of the culvert. It appears that the stream length was shortened by cutting off a large radius meander when the road crossing was constructed originally. Both reference reaches are situated outside of the apparent realignment reach. The channel morphology is judged to be generally stable, consistent with Stage I of Schumm et al.'s (1984) Channel Evolution Model. Wetland areas without a clearly defined channel upstream of the crossing consist of Stage Zero anastomosing grass wetland in the framework of Cluer and Thorne (2014).

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BFW was measured at two locations each upstream and downstream of the crossing (Figure 17). Table 3 summarizes BFW measurements taken during the May 14 site visit, which were used to determine the design BFW. The measured BFWs resulted in a design average BFW of 18.0 feet. In comments on the initial draft of this report, WDFW noted measurements performed upstream ranged between 16 feet and 18 feet (Appendix J). However, these values are wider than predicted by WDFW's regional regression equation C.1 in the WCDG, which results in an estimated BFW equal to approximately 13 feet. The 18 feet value is also larger than in another nearby stream slated for culvert replacement (WDFW site 991501, where BFW=15 feet) that has a larger drainage area and 2-year flood.

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WSDOT also surveyed representative cross sections at four other locations for developing the hydraulic models; two were surveyed upstream and two were surveyed downstream. The two cross sections surveyed downstream are located at WSDOT Station (STA) 0+22 and STA 1+87, where STA 0+22 is located in Reference Reach 2. Both of these cross sections are characterized by vertical banks about 2 feet in height and a defined channel with a flat right floodplain and a sloped left floodplain. The two cross sections surveyed upstream were located at STA 4+15 and STA 5+69, where STA 4+15 is located in reference reach 1. The cross-sections' BFW dimensions range between approximately 13-25 feet, comparable to the BFW measurements (Figure 18). The width-to-depth ratio at STA 4+15, the cross section in reference reach 1, is approximately 8:1.

Given that the BFW is generally narrower downstream than upstream, and the 18 feet value is likely conservative overall, this value was ultimately proposed as a design criterion. The value was accordingly approved by the Quinault Indian Nation and WDFW during a meeting held on June 9, 2021.

Table 3: Bankfull width measurements

BFW #	Width (ft)	Included in Average	Concurrence Notes
1	25.0	Yes	
2	19.0	Yes	
3	14.0	Yes	
4	14.0	Yes	
Average	**18.0**		**Consistent with WDFW estimate**

Figure 15: Upstream Reference Reach 1, looking downstream towards U.S. 101

Figure 16: Downstream Reference Reach 2, looking downstream

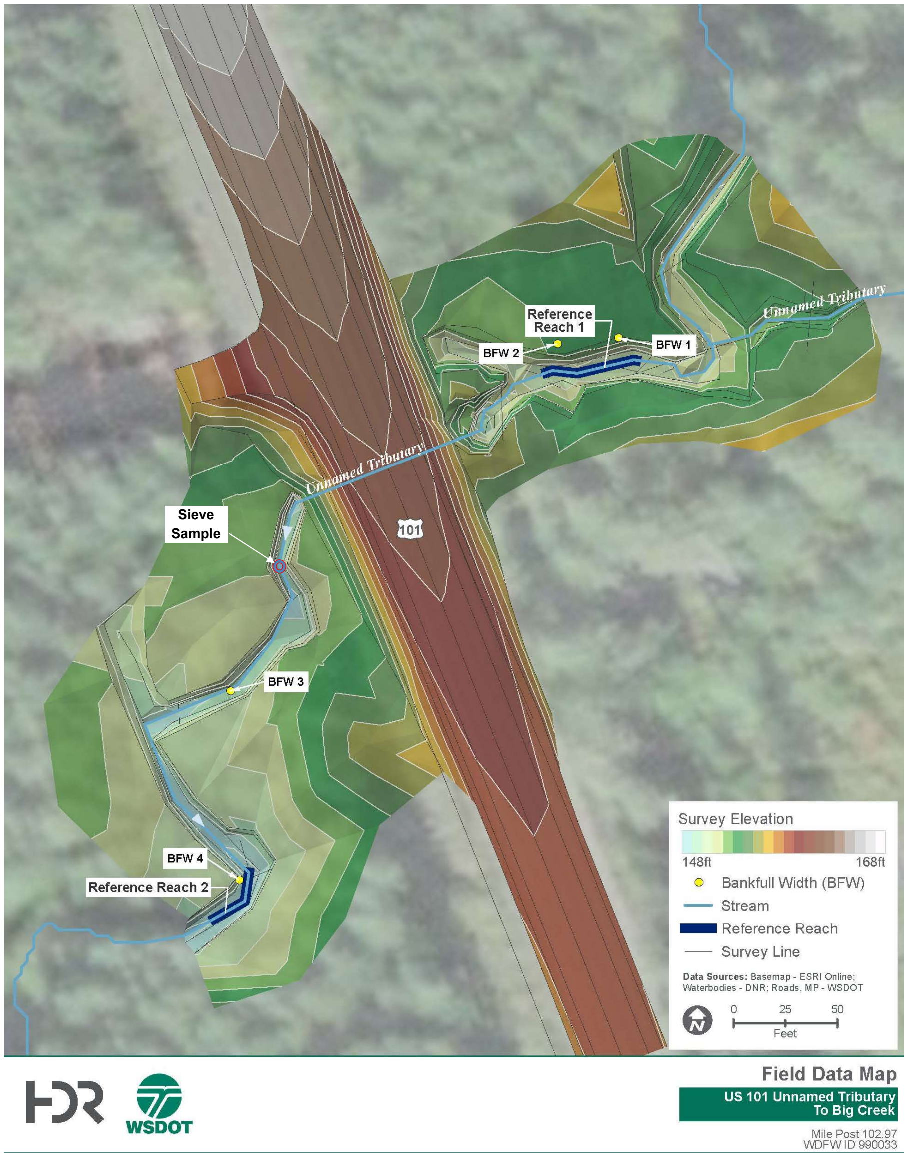

Figure 17: Reference reach and locations of BFW measurements and substrate sampling

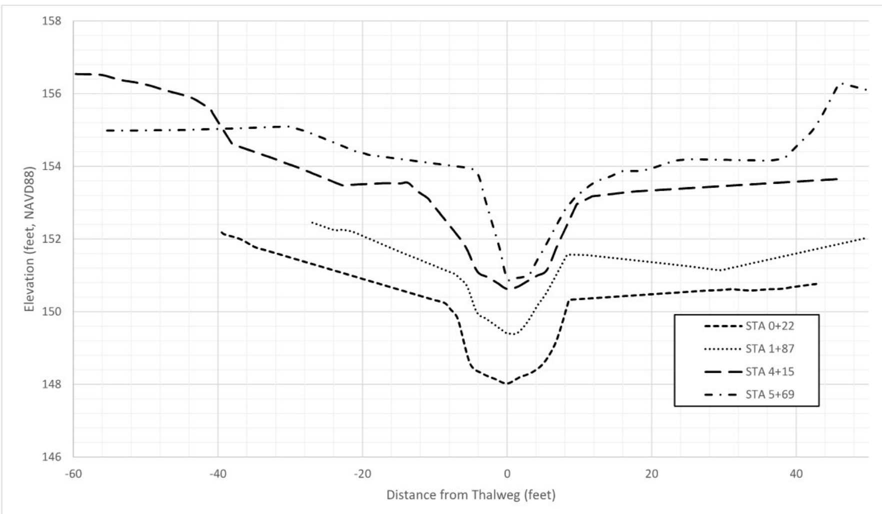

Figure 18: Existing cross-section examples

2.8.3 *Sediment*

Field observations and the land cover data indicate there are lower gradient wetlands upstream of the crossing that likely limit sediment transport and thus supply rates to the project site (Section 2.1). Field observations noted that the grade control at Station 29+25 upstream of the culvert currently limits the transport of coarse bed material downstream. Mobile sediments appear to consist of mostly fines, although there are some patches of small gravel (Figure 19). A bulk surface sample was collected from a heavily embedded gravel patch on a hydraulic control downstream of the culvert (cf. Figure 16), dried, sieved, and weighed. The sample grain size distribution is summarized in Table 4. This grain size distribution is comparable to that found in the nearby stream under crossing 991501, which also drains through glacial outwash, and thus appears to be a characteristic gravel size for the basin.

Table 4: Grain size distribution of bulk surface gravel sample collected downstream of culvert

Sediment size	Diameter (in)
$\mathbf{D_{16}}$	0.1
$\mathbf{D_{50}}$	0.5
$\mathbf{D_{84}}$	1.9
$\mathbf{D_{95}}$	2.7
$\mathbf{D_{100}}$	3.2

Figure 19: Example of streambed material

2.8.4 *Vertical Channel Stability*

Vertical channel stability was assessed considering land use, longitudinal channel elevation profiles of the project stream, topographic models, and field observations. It may be assumed that historical land use in the watershed caused changes in sediment supply, wood loading, and runoff to a greater extent than what may be expected in the future. This is because there is a low potential of landslides or debris flow type sediment delivery in the watershed (Section 2.2), and we may expect declining influence of future forest harvest activities. Historical logging within the riparian zone and clearcut logging likely created historic spikes in sediment supply and greater runoff. With more conservative timber harvest practices and associated protective buffer width requirements in effect since 2005, future sediment yield is expected to decline and return to a lower background level

Longitudinal profiles were developed from 2019 light detecting and ranging (LiDAR) data (Figure 20; USGS and Quantum Spatial 2019). 2020 survey data collected by WSDOT indicates that the channel elevations in the LiDAR data profile are higher than actual, but the bias appears to be consistent away from the road prism. The profiles were used to identify significant landmarks and breaks in the channel gradient along the tributary that would influence spatial variation in sediment transport and deposition patterns which could be associated with a potential for future aggradation or degradation in the vicinity of the replacement structure. This knowledge is primarily important for designing the streambed longitudinal profile within the area of project effects, and the freeboard elevation and foundation depth of the replacement structure

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Upstream of the US 101 crossing the average gradient is 0.6 percent. The deviations in the profile between Stations 900 and -150 are a result of the channel modifications and will be discussed below. Downstream the gradient averages 0.7 percent. That gradient increases to 0.9 percent before reaching an oversteepened segment that is 1250 feet downstream of the crossing. In general, the profile inflections profile depicted in Figure 20 suggests that channel degradation is possible. There is a second culvert, 900 feet upstream, likely constructed for logging in the early 19th century. The consistent grade upstream and downstream of this culvert suggests it hasn't substantially impacted channel instability locally.

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There are convexities in the longitudinal profile upstream and downstream of the project site that warranted evaluation. One is a grade control 40 feet upstream of the crossing, and the other is an over-steepened segment 1250 feet downstream as the project stream approaches Big Creek. Both appear to have been relatively resistant to erosion over an engineering (vs. geological) timeframe. The knickpoint forming the over steepened segment above the confluence with Big Creek is estimated to have progressed on the order of 800 feet upstream over the last 16,000 years (the Holocene). This suggests the underlying material is strongly erosion resistant and that propagation of the knickpoint over 1000 ft upstream to the US101 crossing over an engineering timescale is highly unlikely.

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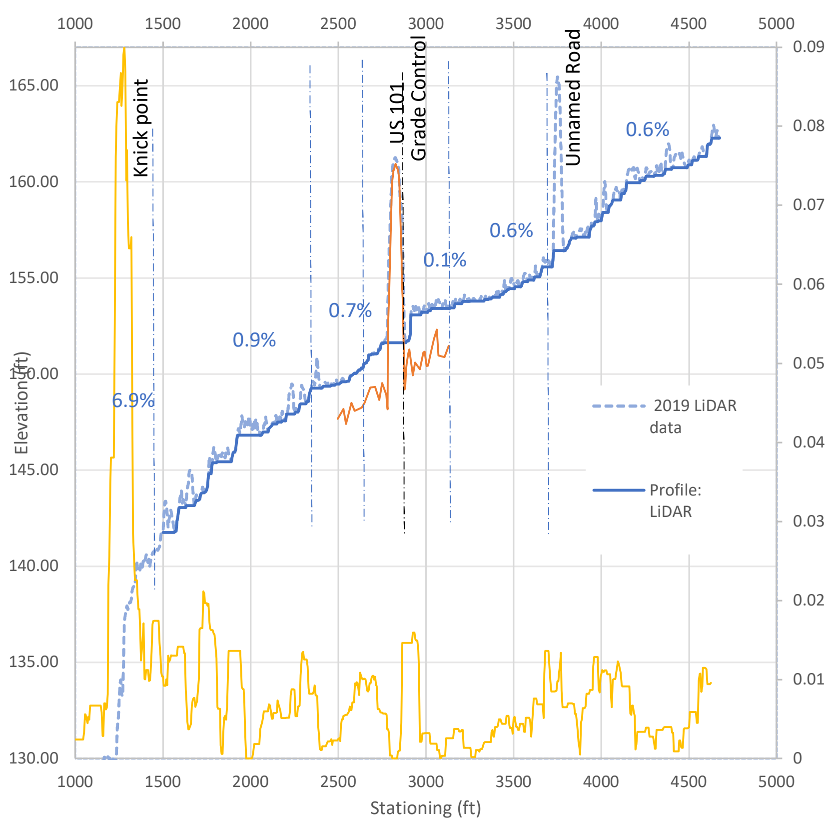

Figure 20: Watershed-scale longitudinal profile

It appears the steep gradient (4 percent) between the grade control and the culvert has remained fairly stable over time (Figures 7 and 20). There were no clear field indicators of incision/degradation of the channel at the grade control, even though the channel appears to have been excavated for routing flows to the present US 101 culvert, as evidenced by the dead-end channel split to the right at the grade control. This inference is supported by high floodplain connectivity of the channel upstream of the grade control feature. This grade control appears to help to maintain wetlands and off-channel habitat.

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Even though it appears from the topography that the pre-development channel may have been shortcut during road construction and thus artificially steepened in the vicinity of the culvert, several factors lead us to conclude that the risks of aggradation or degradation are both negligible for this site: The long profile data indicate that the channel grade is generally consistent upstream and downstream of the culvert. There are no significant discontinuities in the LiDAR profile downstream of the culvert. The overall grade is slightly steeper downstream of the culvert than upstream, but the lack of erosion of the right bank immediately below the culvert, the low elevation and width of the floodplain, and the presence of multiple exposed hardpan grade controls and debris blockages in the channel downstream indicate velocity magnitudes are low and insufficient to cause significant vertical and lateral erosion during floods.

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Log jams can cause significant localized aggradation (Rapp and Abbe, 2003). However, at this site, the channel's stream power at flood flows is estimated to be too low to transport large wood debris; and the limited course-grain sediment supply will limit aggradation. Therefore, aggradation based on large wood would be limited to wood that falls into the channel and not be expected to exceed the elevation of floodplain features surrounding the channel. Field observations supported this finding; we noted no racking or transport of large woody debris in the recent past.

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Based on the scale of the channel and the observed importance of buried large wood steps downstream of the crossing. We foresee that individual large wood blockages may result in negligible aggradation at the crossing (at most on the order of one foot of aggradation is plausible). The development of such blockages is an unpredictable process depending on the volume and pattern of recruitment of riparian wood to the channel. Because the expected maximum amount of aggradation scales with the size of large wood and relies on stochastic processes, increasing the freeboard of the proposed crossing to also account for future aggradation does not appear to be required at this crossing.

2.8.5 *Channel Migration*

Channel migration was assessed based on topography and field observations. Sinuosity is around 1.3 to 1.4 in the reach, with distinct bends in the channel planform. The stream is too small and canopy too thick for aerial photography to be of use for evaluating migration history. The channel is generally unconfined, streambanks are composed of soft material, and overbank flow is predicted by hydraulic modeling of existing and natural conditions (see Section 4) to occur during relatively frequent recurrence interval flood events. The stream banks are generally densely vegetated with established shrubs and sedges, and there are periodic locations with exposed hardpan along the length of the project reach in sections with well-defined banks. The right bank curves a short distance in front of the culvert outlet with high flows directed at it, yet the bank has not eroded, which indicates velocities through the culvert barrel are relatively low, and insufficient to lead to significant meandering. The channel appears to have stayed generally in place, with no significant relic channels seen other than the segment cut off by culvert construction. Based on these observations, the risk of channel migration appears to be negligible in the vicinity of the culvert.

2.8.6 *Riparian Conditions, Large Wood, and Other Habitat Features*

Upstream of the U.S. 101 crossing, the riparian corridor is mixed forest consisting primarily of alder and some Douglas fir. Beyond the edges of the stream, the forest is primarily stands of young Douglas fir in areas both north and south of the stream corridor that have been clearcut in the past. The channel at the upstream end contains dense growths of aquatic vegetation and flows through a low elevation wetland floodplain overgrown with grasses and sedges. There is fallen timber spanning the floodplain and multiple large snags on the left bank. There is a dense shrub layer with native species including salmonberry, willows, spirea, and sedges and grass. The stream between the culvert and wetlands floodplain consists of a series of deep pools with LWM on both banks and across the channel. There were four places noted where logs and woody material were present in the stream channel and banks. A total of 16 key pieces of LWM was counted, with logs ranging from 6 to 48 inches in diameter, and a large rootwad was present at the bend on the left bank. Measurements of mobile pieces upstream of the culvert indicates that pieces longer than about 9 feet and thicker than about 5 inches in diameter are not transported far and become racked up on larger pieces of wood and brush. Trees that fall into or across the channel remain generally in place.

The downstream reach flows through a mixed mature forest cover within the riparian zone that is predominantly Douglas fir, with some alders and willows. The riparian corridor in the vicinity of the culvert is constrained on the left bank by the presence of the highway. Forest cover downstream consists of an even-aged stand of Douglas fir end, reflecting clearcutting evident in historic aerial photos from the early 1990s. There is abundant LWM in the reach, with four places noted where logs and woody material were present in the stream channel and banks. A total of nine key pieces of LWM was counted throughout the downstream reach, with logs ranging from 5 to 18 inches in diameter. There was abundant small woody debris racked throughout the reach, but mainly near the upstream end. A natural log weir across the channel near the midpoint of the surveyed reach created a small 6-inch hydraulic drop and presented as a grade control.

WDFW completed a physical survey in 2018 at the site and did not note any signs of beaver. Beaver dams and signs of activity were also not observed during any of the site visits.

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3 Hydrology and Peak Flow Estimates

The project stream drains an ungaged basin, with no long-term historical flow data available. No hydrologic studies, models, or reports were found that summarized peak flows in the basin. Consequently, USGS regression equations (Mastin et al. 2016; Region 4) were used to estimate peak flows at the U.S. 101 crossing. Inputs to the regression equation included basin size and mean annual precipitation. The project stream has a basin area of 0.57 square mile above the culvert and a mean annual precipitation within the basin of 106.1 inches (PRISM Climate Group 2019). The watershed was delineated from LiDAR data acquired from the WDNR LiDAR Geologic Information Portal (USGS and Quantum Spatial 2019) using Arc Hydro.

The resulting regression estimates (Table 5) were evaluated for potential sub-regional bias by comparing regression predictions against estimates derived at selected stream gages in the area using available flow records. A Washington Department of Ecology gage was identified from the Wishkah River, but only USGS gages were found with a sufficiently long period of record (>20 years) in the area to permit evaluating the larger predicted flood peaks (Table 6).

Peak flow data were analyzed for each gage following the Bulletin 17B methodology for peak flow frequency analysis, using the Hydraulic Engineering Center's Statistical Software Package (HEC-SSP) version 2.2. HEC-SSP uses the Log Pearson Type III distribution for annual peak flows on unregulated streams, fit by the Method of Moments. Distribution parameters were estimated for the 2-, 10-, 100-, and 500-year return intervals based on moments of the sample data (site-specific). Adjustments were made for non-standard data, low outliers, and historical events. The resulting peak flow estimates were compared against the regression estimates using the equations in Mastin et al. (2016), where drainage area and mean annual precipitation estimates were determined using USGS' StreamStats web application. The ratio of gage-based to regression-based estimates was then plotted against drainage area (Figure 21). The results indicate that the regression estimates for smaller basins may be generally comparable to or higher than would be derived using gage data. As corroboration, a modeling exercise performed for Culvert ID 993704 using the MGS Flood model indicated that the regression estimates for a similarly sized, nearby drainage area were higher than values estimated based on a more direct simulation of stormwater rainfall-runoff processes. The regression estimates accordingly appear to be more conservative.

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Table 5: USGS regression-based estimates of peak flow

Mean recurrence interval (MRI) (years)	USGS regression equation (Region 4) (cfs)	Regression standard error (percent)
2	54.7	52.5
10	94.1	50.5
25	113.0	51.7
50	128.0	52.9
100	145.0	54.2
500	179.0	58.0
2080 predicted 100	169.0	NA

Table 6: Local USGS Gages Used to Evaluate Bias in USGS Regression Predictions

Station #	Gage Name	Years of Record
12039005	Humptulips River Below Hwy 101	2002-2018
12036000	Wynoochee River Above Save Creek Near Aberdeen, WA	1952-2018
12035500	Wynoochee River At Oxbow Near Aberdeen, WA	1925-1952
12035450	Big Creek near Grisdale, WA	1972-1996
12035400	Wynoochee River near Grisdale, WA	1965-2018
12039050	Big Creek near Hoquiam, WA	1949-1970
12039100	Big Creek Tributary near Hoquiam, WA	1949-1968

Consequently, the regression estimates in Table 5 were used in design development, to provide a safety factor when designing for flood conveyance, freeboard, channel stability, and scour. For more information on the 2080 predicted 100-year flow determination see Section 7.2.

Summer low-flow conditions are unknown and high/low fish passage design flows are not included in this analysis. The stream was observed to be dry in mid-August 2021.

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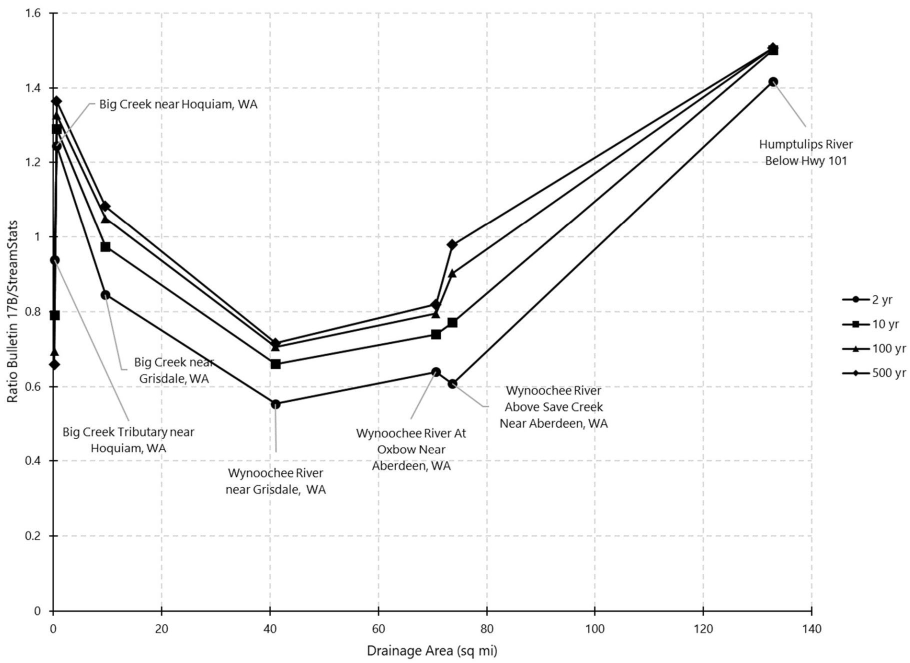

Figure 21: Ratio of gage-based flood peak magnitudes vs. regression-based estimates, plotted against drainage area

4 Hydraulic Analysis and Design

The hydraulic analysis of the existing and proposed U.S. 101 MP 102.97 unnamed tributary crossing was performed using the United States Bureau of Reclamation's (USBR's) SRH-2D Version 3.2.4 computer program, a two-dimensional (2D) hydraulic and sediment transport numerical model (USBR 2017). Pre- and post-processing for this model was completed using SMS Version 13.1.11 (Aquaveo 2018).

Three scenarios were analyzed for determining stream characteristics for the UNT with the SRH-2D models: (1) existing conditions with the pipe arch, (2) natural conditions with the roadway embankment removed and the channel graded, and (3) future conditions with the proposed 24-foot hydraulic opening.

4.1 Model Development

This section describes the development of the model used for the hydraulic analysis and design.

4.1.1 *Topographic and Bathymetric Data*

The channel geometry data in the model were obtained from MicroStation and InRoads files supplied by the Project Engineer's Office (PEO), which were developed from topographic surveys performed by surveyors hired by WSDOT prior to March 13, 2020. The survey data were supplemented with 3-foot resolution LiDAR data (USGS and Quantum Spatial 2019). Proposed channel geometry was developed from the proposed grading surface created by HDR and later updated by Kleinschmidt. All survey and LiDAR information is referenced against the North American Vertical Datum of 1988 (NAVD88) in US survey feet.

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Measurements of downstream flow obstructions within the main channel were taken during the June 15, 2021 site visit and were incorporated into the proposed-conditions mesh to determine the backwater effect of downstream obstructions on the hydraulic structure. The percent of bankfull area blocked by the obstructions were estimated based on field observations and an equivalent crest elevation was determined that obstructs the estimated percent of bankfull area. Node elevations within the mesh were manually raised to the specified crest elevation at approximate locations of the obstructions observed in the field. Of the three obstructions observed in the field, two become irrelevant for the proposed conditions due to the new alignment of the crossing and were omitted from the model. The last obstruction was incorporated into the model approximately 85 feet downstream of the proposed crossing as an equivalent crest determined for a 35% blockage of the bankfull area of the channel.

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4.1.2 *Model Extent and Computational Mesh*

The hydraulic model upstream extents begin with the detailed survey data and start approximately 230 feet upstream of the existing culvert inlet. The detailed survey data end approximately 290 feet downstream of the existing culvert outlet, measured along the channel centerline. Model extents upstream and downstream were limited to the survey reach because of elevation inconsistencies between the survey and LiDAR data. LiDAR data were used to supplement topographic data outside of the lateral survey extents in order to contain the existing inundation limits upstream of the culvert.

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The computational mesh elements are a combination of patched (quadrilateral) and paved (triangular) elements. Finer resolution was used in the channel (with the exception of large pools) and wherever else it was simple to use quadrilateral elements, while larger elements were used in the floodplain. The existing-conditions mesh covers a total area of 291,821 square feet (SF), with 8,565 quadrilateral and 28,656 triangular elements (Figure 22). The natural-conditions mesh covers a total area of 291,821 SF, with 9,586 quadrilateral and 23,426 triangular elements (Figure 23). The proposed-conditions mesh covers a total area of 291,821 SF, with 8,241 quadrilateral and 23,417 triangular elements (Figure 24).

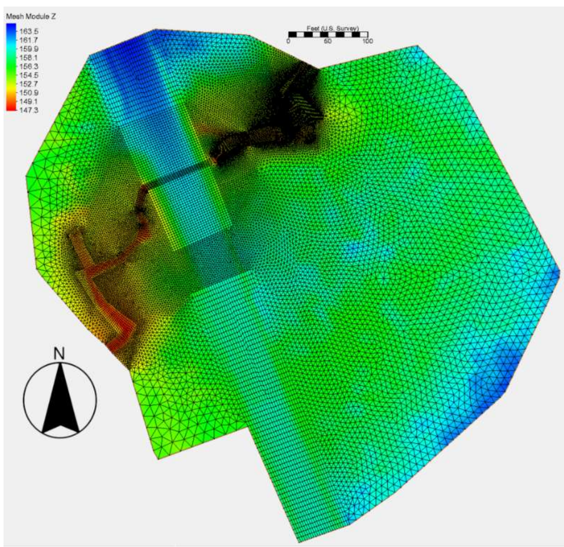

Figure 22: Existing-conditions computational mesh with underlying terrain

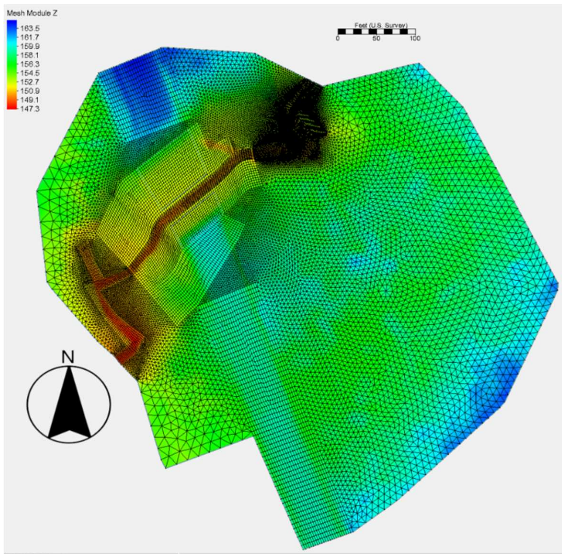

Figure 23: Natural-conditions computational mesh with underlying terrain

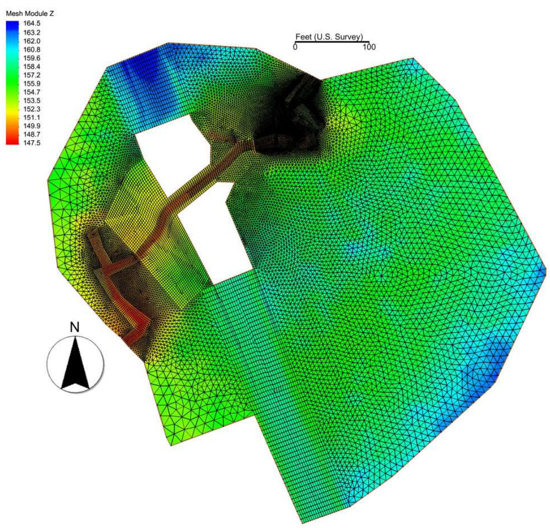

Figure 24: Proposed-conditions computational mesh with underlying terrain

4.1.3 ***Materials/Roughness***

Manning's n values were estimated for the natural channel and floodplain of the project stream using the Cowan method based on site observations (Arcement and Schneider 1989; see Appendix G). The resulting values are consistent with standard engineering values for 1-D simulations (Barnes 1967). Because bank stabilizing vegetation is not expected to grow inside the structure, the channel there will have a dominant bed material composed of gravel and small cobble. The value for the culvert was estimated using the same reference, with a base value of n=0.035 for a gravel-cobble mix, and with 0.01 added to account for low profile bedforms that will be part of the final design (see Section 4.4). The resulting 1-D values were then adjusted down by 10 percent to reflect generally expected reductions when moving to a 2-D model parameterization (Robinson et al. 2019; Table 7). Figures 25-27 depict the model spatial distributions of hydraulic roughness coefficient values for existing, natural, and proposed conditions, respectively.

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Table 7: Manning's n hydraulic roughness coefficient values used in the SRH-2D model

Land cover type	Manning's n
Stream Channel	0.101
Within Proposed Crossing	0.041
Floodplains	0.112
Roadway	0.02

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Figure 25: Spatial distribution of roughness values in SRH-2D existing-conditions model

Figure 26: Spatial distribution of roughness values in SRH-2D natural-conditions model

Figure 27: Spatial distribution of roughness values in SRH-2D proposed-conditions model

4.1.4 *Boundary Conditions*

Model simulations were performed using constant discharges ranging from the 2-year to 500-year peak flow events summarized in Section 3. External boundary conditions were applied at the upstream and downstream extents of the model domain and remained the same between the existing-, natural- and proposed-conditions runs. A constant flow rate was specified at the upstream external boundary condition to represent the single tributary, while a normal depth rating curve was specified at the downstream boundary. The downstream normal depth boundary condition rating curve at the channel exit was developed within SMS using the existing terrain, assuming a downstream slope of 0.6 percent as measured from the survey and a composite roughness of 0.121 (Figures 28, 29). During the existing-conditions 500-year simulation there is substantial backwatering from the existing crossing that causes flow to leave the model domain via the roadway shoulder for roadside drainage at the southern end of the model domain. A normal depth rating curve was specified at this location and was developed within SMS using the existing terrain, assuming a downstream slope of 0.1 percent as measured from LiDAR and a composite roughness of 0.03 (Figures 30, 31). A sensitivity analysis on the downstream boundary condition was performed to obtain an accurate representation of the water surface profile and to determine if the boundary condition assumption affected hydraulics within the U.S. 101 crossing project extents. Variations in results due to this sensitivity analysis did not propagate sufficiently upstream to impact hydraulic conditions at the existing crossing. Model simulations were run for a sufficiently long duration until the results stabilized across the model domain.

An HY-8 internal boundary condition was specified in the existing-conditions model to represent the existing corrugated metal pipe culvert crossing. The existing crossing was modeled within HY-8 as a 44.4-by-72.2-inch pipe. This was the closest available pipe arch size configuration within HY-8 as compared to the measured 43-by-73 inch existing structure. A Manning's roughness of 0.024 was assigned to the culvert. The culvert was assumed to be unobstructed and free from any stream material within the barrel. HY-8 boundary conditions are summarized in Figure 32.

A symmetry (slip) boundary condition was specified in the proposed-conditions model to better represent flow inside the proposed structure. Under default conditions, SMS assumes a no-slip (0 foot per second [ft/s]) condition at the edges of the mesh. The boundary layer of 0 ft/s would be very thin against the smooth structure surface. The mesh is too coarse to accurately capture the boundary layer; therefore, it is more appropriate to use a slip boundary condition, which does not force velocities to 0 ft/s at the mesh boundary. The wingwalls were incorporated into the geometry of the slip boundary condition to simulate the constriction induced by the wingwalls at the upstream entrance of the proposed crossing.

The locations of boundary conditions in the existing, natural, and proposed conditions models are depicted in Figures 33, 34, and 35, respectively.

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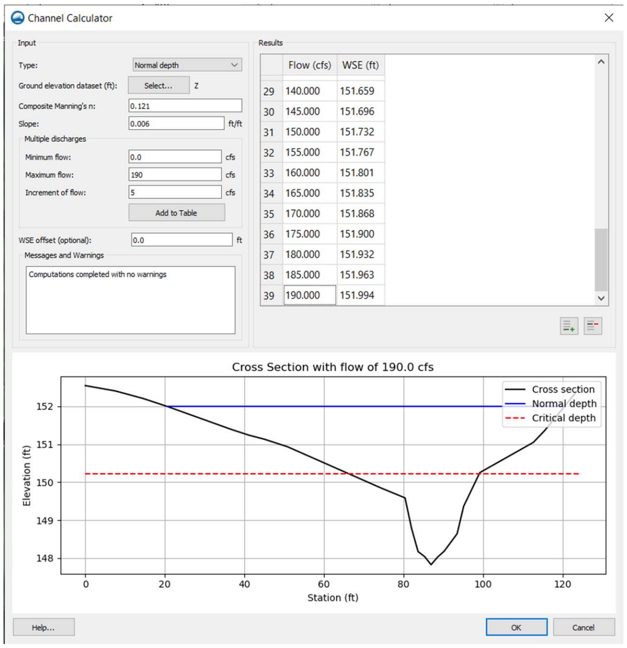

Figure 28: Channel downstream boundary condition input

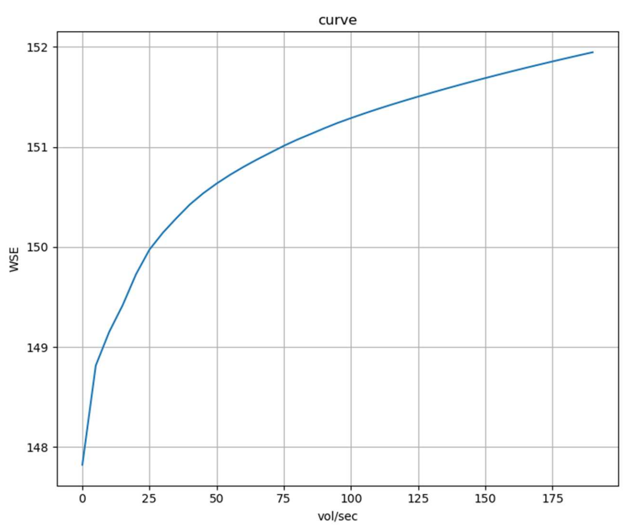

Figure 29: Channel downstream normal depth rating curve

Figure 30: Roadside drainage downstream boundary condition input

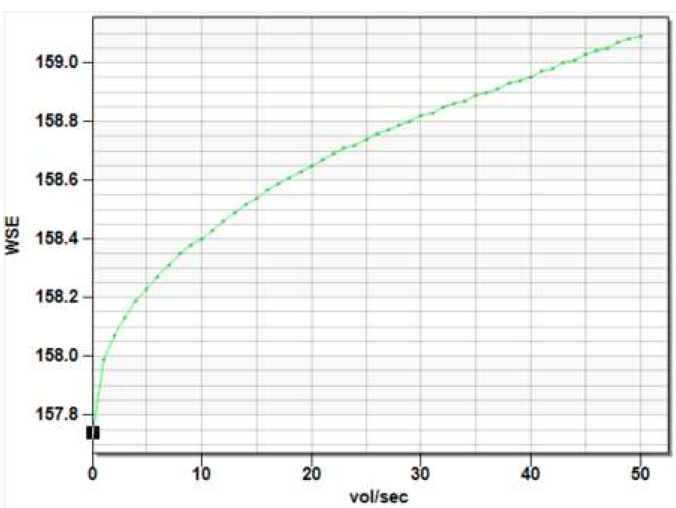

Figure 31: Roadside drainage downstream normal depth rating curve

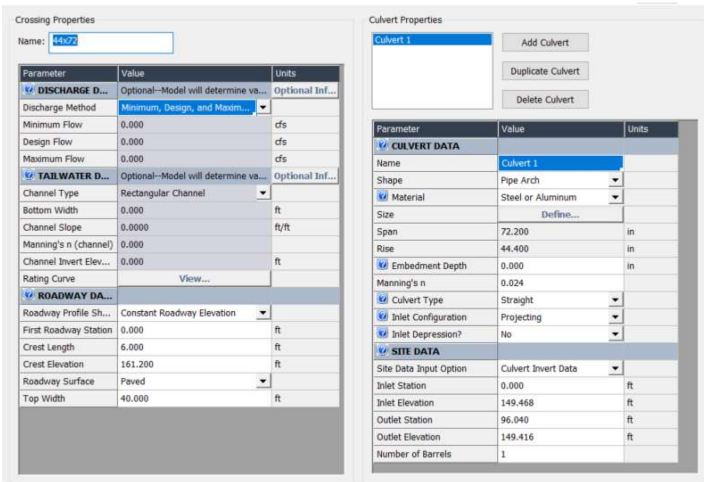

Figure 32: HY-8 culvert parameters

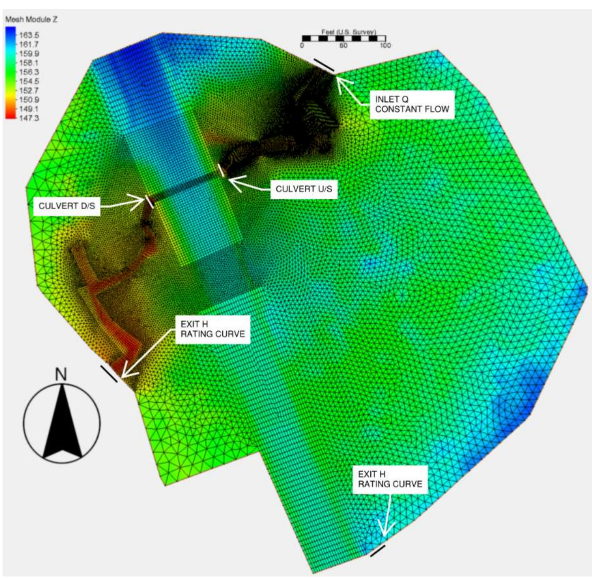

Figure 33: Location of boundary conditions for the existing-conditions model

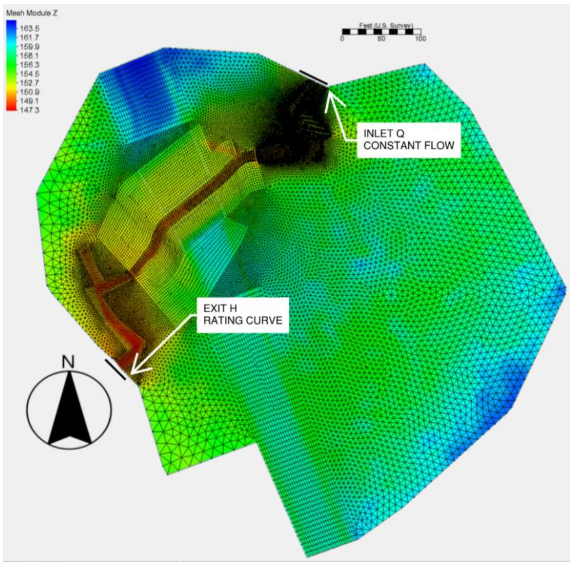

Figure 34: Location of boundary conditions for the natural-conditions model

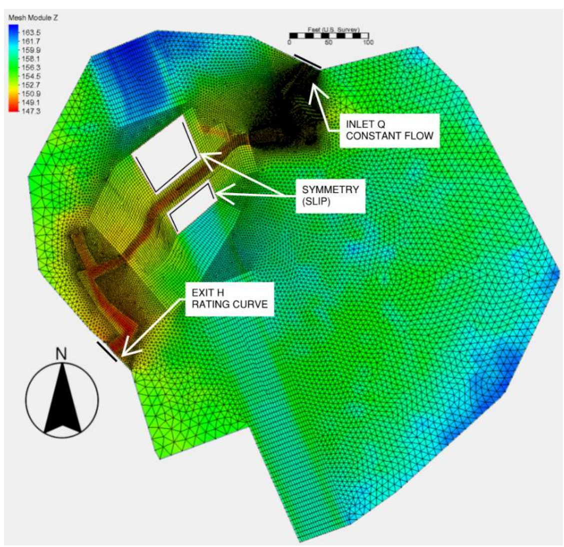

Figure 35: Location of boundary conditions for the proposed-conditions model

4.1.5 *Model Run Controls*

Similar model run controls were used for every scenario with the exception of the existing-conditions 100-year and 500-year events. In these two cases, the simulation time was increased to 5.0 hours to ensure flow continuity between upstream and downstream. Figure 36 depicts the model controls for all other runs, which used a simulation time of 2.5 hours. The result output frequency used was once per minute (0.016 hour) to begin with to troubleshoot the model, and graduated to every 15 minutes (0.25 hour) once the model was stable.

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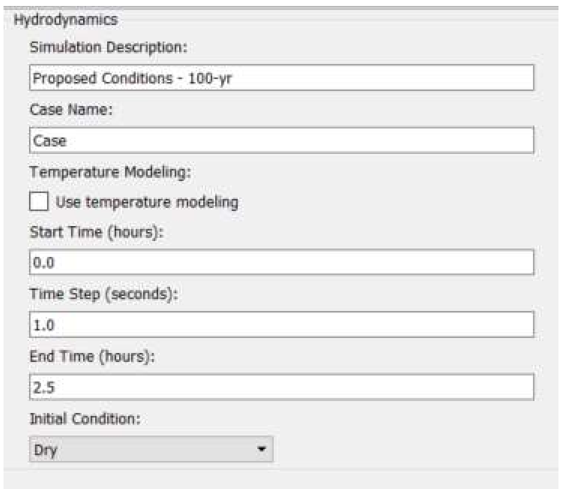

Figure 36: Model controls with dry initial conditions

4.1.6 *Model Assumptions and Limitations*

The SRH-2D hydraulic model was developed to determine the minimum hydraulic structure opening, establish the proposed structure low chord elevation (and associated freeboard), and characterize hydraulic parameters used to design the crossing, streambed, and LWM. There are several attributes of the data relied upon to develop the model that affect the resolution to which model output should be relied on. In particular, the survey data collected for developing the model terrain geometry were sufficient to capture macroscale variation in channel form and floodplain topography on the order of average channel width/depth/location and floodplain gradients. The spatial scatter of the survey point data was too coarse, however, to develop a model terrain capable of discerning an accurate and precise resolution of velocity distributions at smaller microtopographic scales, precluding predicting rapid spatial variation in hydraulic properties in association with bedform and instream roughness and flow obstruction variation. Accordingly, the designs are based on general, spatially averaged model predictions of velocity and shear stress, with an appropriate safety factor. Small scale variations in hydraulic properties should not be interpreted as signifying a meaningful feature of the design, Highly detailed design modeling of large wood structures is therefore not warranted, where structure stability and scour can be designed sufficiently using simply water depth and average channel values of velocity predicted by the model and increasing roughness locally.

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In addition, the topographic extent of the area surveyed did not extend beyond the model predictions of inundation extent for the most extreme flood events, where the flooding extended onto areas of the adjoining surface generated from the LiDAR data. As seen in Figure 20, the LiDAR data appear to be biased high along the stream channel. This results in artificially concentrating flood flows onto the area within the bounds of the survey, and thus potentially over-predicting water surface elevations.

The use of a steady peak inflow rate is an appropriate assumption to meet design objectives at this site. Using a steady peak inflow rate provides a conservative estimate of inundation extents and water surface elevation (WSEL) associated with a given peak flow, which is used to determine the structure size and low chord. Similarly, the model predictions of peak velocity are used to design general channel morphology, streambed composition, and both loose and fixed LWM stability. Each scenario is run for a sufficient time to fill storage areas and for WSELs to stabilize until flow upstream equals flow downstream. This modeling method does not account for the attenuation of flow that will impact the actual upstream and downstream hydrographs as influenced by the amount of storage upstream of the existing undersized culvert. Nonetheless, during an actual runoff event, it is unlikely that the area upstream of the culvert would fill up entirely. An unsteady simulation could be used to route a hydrograph through the model to estimate peak flow attenuation for existing and proposed conditions. During an unsteady simulation, the areas upstream of the existing culvert would act as storage and, as a result, the flow downstream of the crossing would likely be less than the current design peak flow event. This is expected to be less of an issue for the natural conditions and proposed PHD scenarios at this site, however, where the channel size is small relative to the hydraulic opening, and the channel slope too steep, for flow attenuation effects to be significant.

The SRH-2D model outputs an estimate of shear stress that is calculated using a 2-D vector adaptation of the 1-D uniform flow approximation based on depth and energy slope. The program substitutes Manning's equation to calculate the slope, which results in shear stress estimate being proportional to the square of the Manning's n coefficient. Because Manning's n is used in the modeling as a surrogate for various energy losses n addition to grain friction, the resulting estimates of shear stress cannot be used to size streambed substrates or evaluate local scour depth. Values are presented in this report for general reference, but should be treated generally as substantial over-estimates of the actual boundary shear stress (e.g., Pasternack et al. 2006). This is addressed directly in Section 5.1.

The model results and recommendations in this report are based on the conditions of the project site and the associated watershed at the time of this study. Any modifications to the site, man-made or natural, could alter the analysis, findings, and recommendations contained herein and could invalidate the analysis, findings, and recommendations. Site conditions, completion of upstream or downstream projects, upstream or downstream land use changes, climate changes, vegetation changes, maintenance practice changes, or other factors may change over time. Additional analysis or updates may be required in the future as a result of these changes.

4.2 Existing–Conditions Model Results

Hydraulic results were summarized and compared at specific locations for the existing-conditions. Locations of the cross sections used for reporting results for existing-, natural-, and proposed-conditions models are depicted in Figure 37. Three cross sections are located upstream and three are located

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downstream, with one in the center of the existing culvert and proposed structure. The longitudinal profile stationing is depicted in Figure 38.

Existing-conditions hydraulic results across the main channel are summarized for the upstream and downstream cross sections in Table 8. Average velocities across the main channel, left overbank (LOB), and right overbank (ROB) of each cross section for the 100-year flow are shown in Table 9. Under existing conditions, the culvert does not have capacity to convey the design flow beyond the 2-year flow event. This causes backwater to fill the area upstream for the range of flows simulated (Figure 39). Pressure flow conditions first occur when the headwater elevation exceeds 153.2 feet. By comparison, the 2-year flow event WSEL at the culvert inlet is 153.1 feet. The U.S. 101 roadway overtops during the 500-year event, approximately 220 feet to the south of the existing crossing. Additionally, the high WSEL for the 500-year event causes some overflow into the adjacent, southern basin via the upstream side roadway ditch (Figure 40).

Typical cross sections for downstream and upstream are found in Figures 41 and 42, respectively. The downstream cross section shows a channel that, while confined, has an accessible floodplain. The upstream cross section shows an unconfined channel spreading flow into the floodplains at low flows. All cross sections were drawn perpendicular to flow. The 100-year velocity map for existing conditions can be seen in Figure 43. All cross sections are presented in Appendix C.

As a result of the insufficient capacity of the existing pipe arch culvert, the upstream hydraulics are significantly influenced. As expected, depths are greater than the downstream reach and velocities and shear values are comparatively lower (within the limits of backwater). When looking at the entire model domain, the largest velocities occurred in the downstream reach and at localized channel bends, where no backwater is present, and the flow is more confined than in the upstream cross sections.

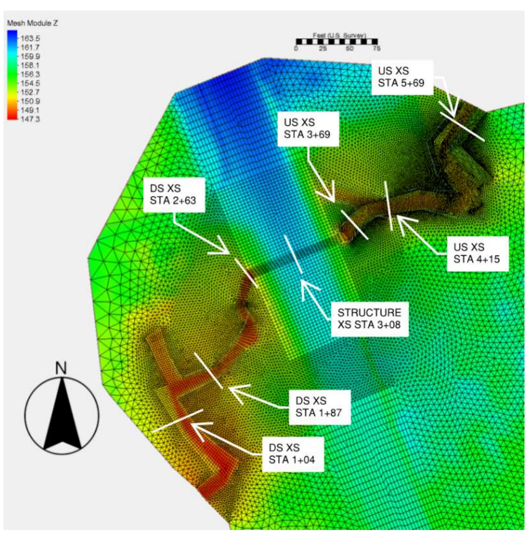

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Figure 37: Locations of cross sections used for results reporting for existing-, natural-, and proposed-conditions models

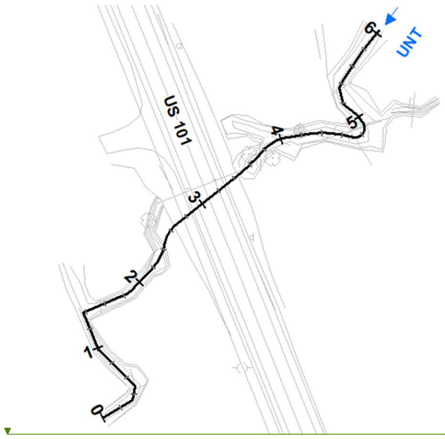

Figure 38: Longitudinal profile stationing for existing, natural, and proposed conditions

Table 8: Hydraulic results for existing conditions within main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	500-year
Average WSEL (ft)	1+04.02	151.1	152.0	152.2
	1+86.48	151.6	152.3	152.5
	2+63.12	152.6	153.4	153.5
	3+69.72	153.1	157.1	158.8
	4+15.89	153.5	157.1	158.8
	5+69.03	154.1	157.1	158.8
Maximum water depth (ft)	1+04.02	2.8	3.7	3.9
	1+86.48	2.2	3.0	3.1
	2+63.12	4.5	5.4	5.6
	3+69.72	2.6	6.6	8.3
	4+15.89	2.8	6.5	8.2
	5+69.03	3.2	6.2	7.9
Average velocity magnitude (ft/s)	1+04.02	1.6	1.9	1.9
	1+86.48	1.9	2.4	2.5
	2+63.12	1.1	2.3	2.7
	3+69.72	1.7	1.0	1.0
	4+15.89	1.2	0.5	0.3
	5+69.03	1.3	0.7	0.5
Average shear stress (lb/SF)	1+04.02	0.7	0.8	0.8
	1+86.48	1.0	1.3	1.3
	2+63.12	0.3	1.2	1.6
	3+69.72	0.7	0.2	0.2
	4+15.89	0.4	<0.1	<0.1
	5+69.03	0.5	<0.1	<0.1

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Table 9: Existing-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main ch.	ROB [a]
1+04.02	1.3	1.9	0.8
1+86.48	0.9	2.4	0.8
2+63.12	0.9	2.3	0.3
3+69.72	0.2	1.0	0.2
4+15.89	0.2	0.5	0.2
5+69.03	0.3	0.7	0.6

a. ROB/LOB locations were approximated at the tops of banks from inspecting the surface and 2-year top width.

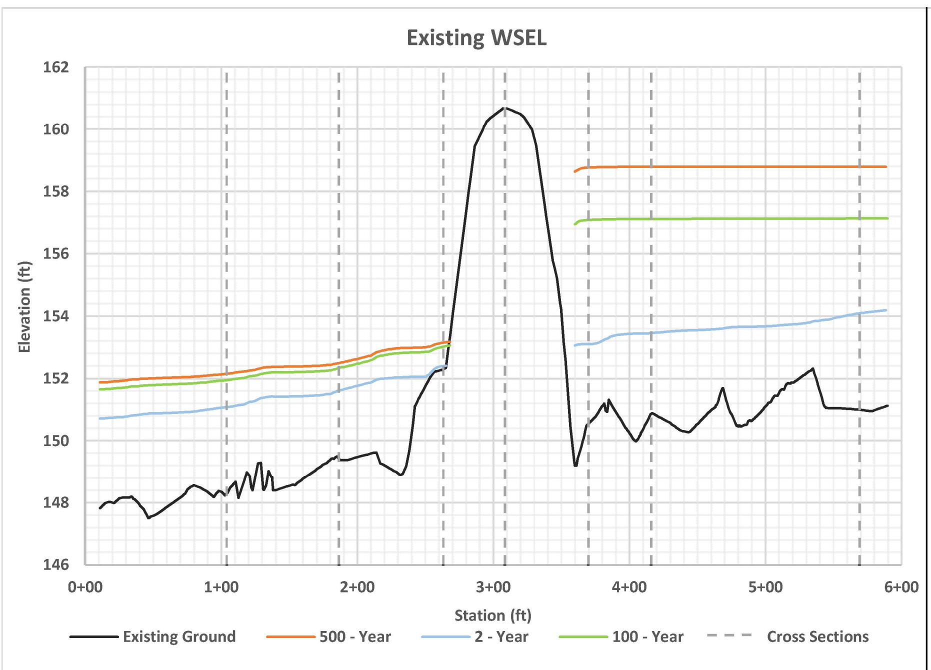

Figure 39: Existing-conditions water surface profiles

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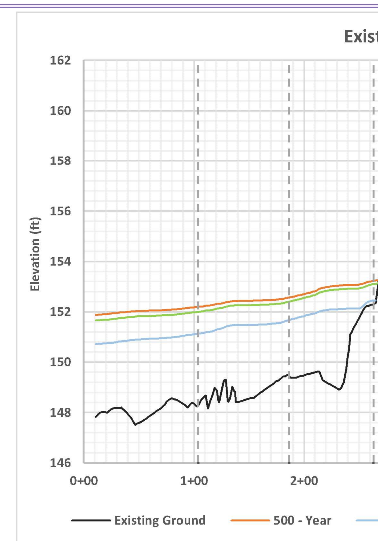


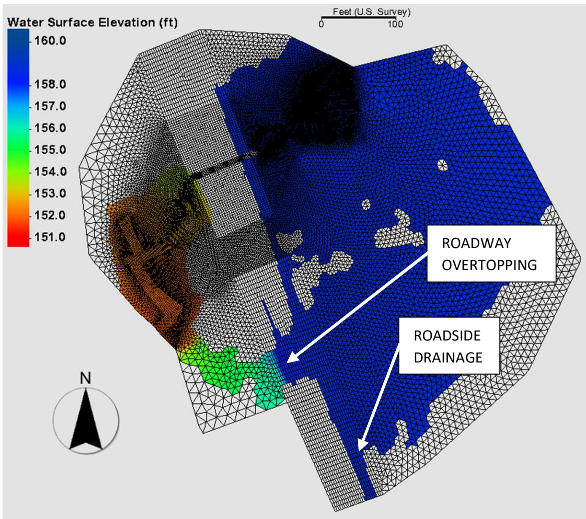


Figure 40: Road overtopping and roadside drainage at existing-conditions 500-year flow event

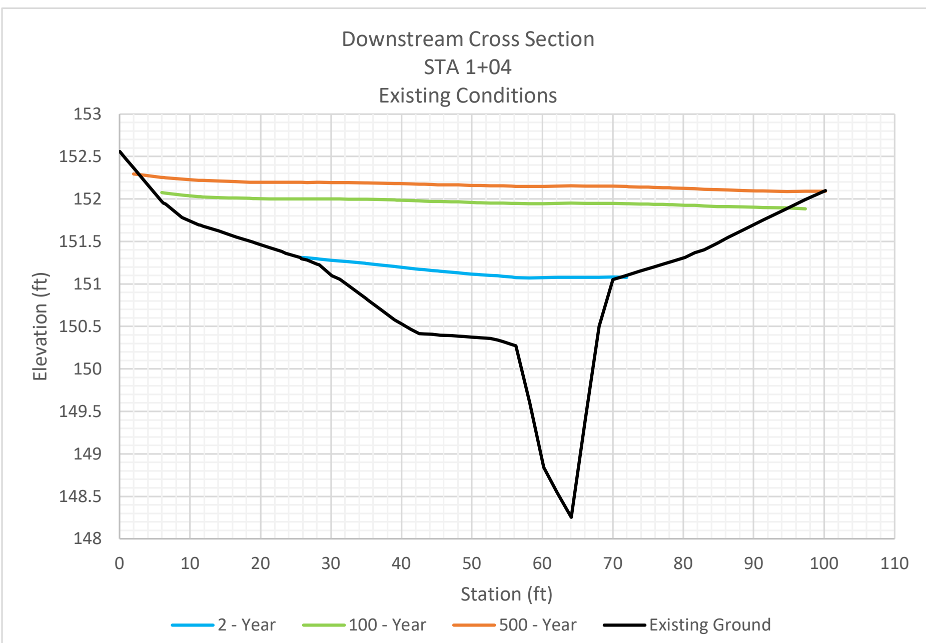
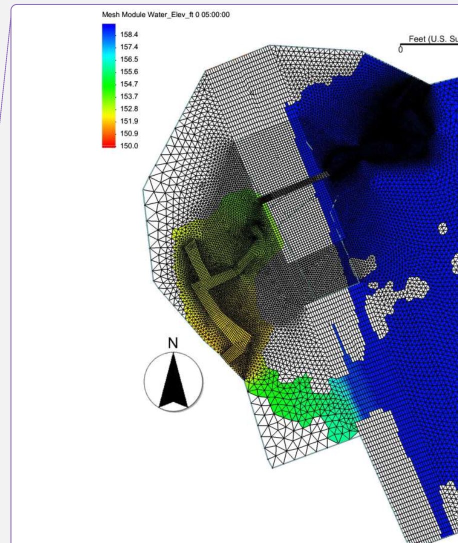


Figure 41: Typical downstream existing-conditions channel cross section (STA 1+04)



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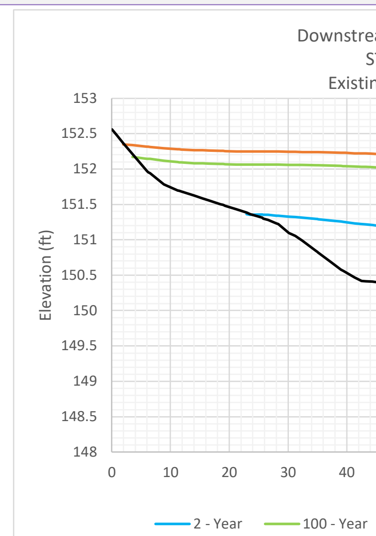

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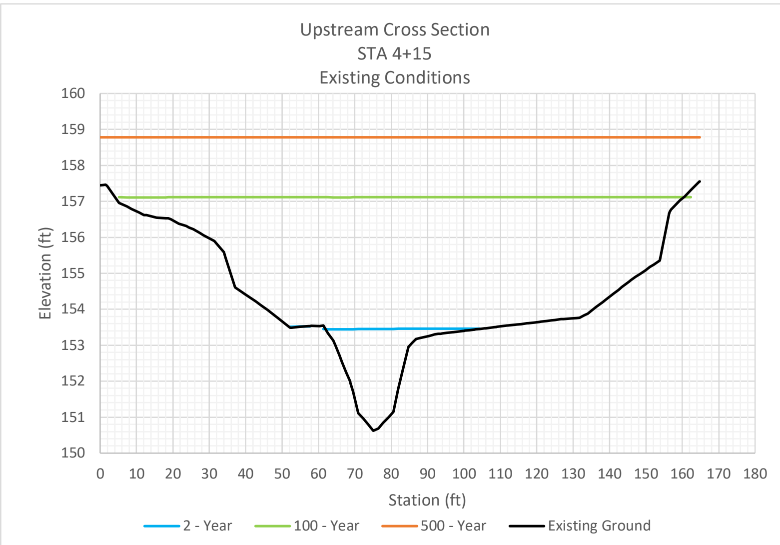

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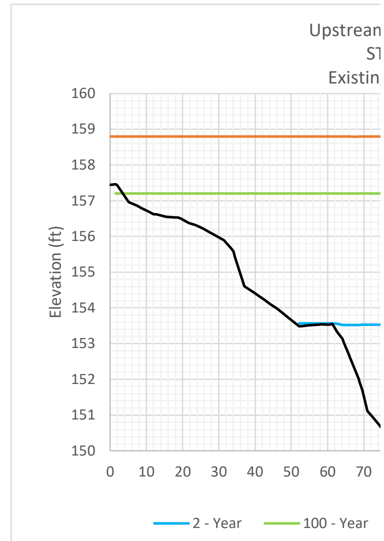
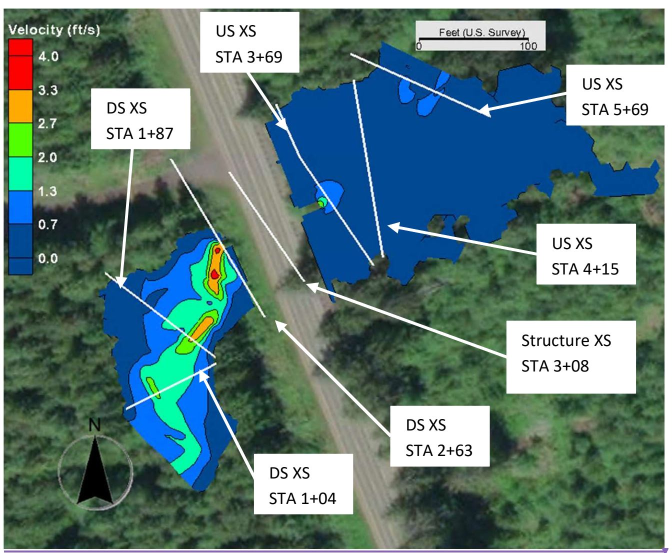


Figure 42: Typical upstream existing-conditions channel cross section (STA 4+15)



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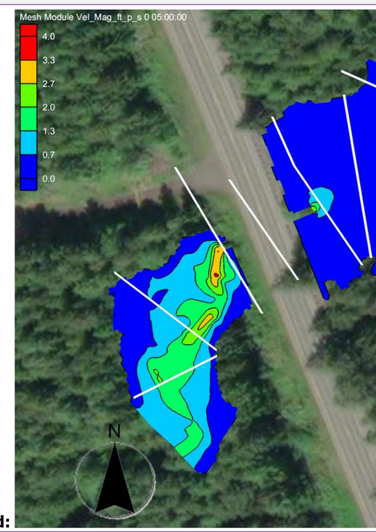

Figure 43: Existing-conditions 100-year velocity map with cross-section locations

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4.3 Natural–Conditions Model Results

Hydraulic modeling results for the main channel are summarized for natural-conditions in Tables 10 and 11. The proposed project alignment, also utilized for natural-conditions modeling, was realigned from the existing alignment to shorten the culvert and align the streambed grade in line with upstream. Under natural conditions, the crossing does not backwater or overtop the smaller unnamed roadway heading west off of U.S. 101. However, flow is still spread across the floodplain in the upstream, unconfined channel because of accessible floodplains. The WSELs for the range of flows simulated are depicted along the longitudinal profile in Figure 44. Typical cross sections for downstream and upstream are found in Figures 45 and 46, respectively. All cross sections are provided in Appendix C. Figure 47 depicts the predicted velocity map for the 100-year flood peak. Depths during the 100-year flood peak are similar upstream and downstream. The similarities in velocity are driven primarily by the shallow, uniform slope and a consistent channel geometry and roughness. Under natural conditions, the upstream reach is not influenced by the existing culvert and, therefore, the upstream and downstream hydraulics become more closely aligned. When looking at the entire model domain, the largest velocities occur outside of the limits of proposed improvements at isolated locations upstream and downstream, primarily at sharp channel bends.

Table 10: Hydraulic results for natural conditions within main channel

Hydraulic parameter	Cross-section (STA)	2-year	100-year	2080 predicted 100-year	500-year
Average WSEL (ft)	1+04.02	151.1	152.0	152.1	152.2
	1+86.48	151.6	152.3	152.5	152.5
	2+63.12	152.2	153.1	153.2	153.2
	3+08.39 [a]	152.5	153.4	153.5	153.6
	3+69.72	152.8	153.7	153.9	153.9
	4+15.89	153.1	154.0	154.1	154.2
	5+69.03	154.0	154.9	155.1	155.1
Maximum water depth (ft)	1+04.02	2.8	3.7	3.9	3.9
	1+86.48	2.2	3.0	3.1	3.1
	2+63.12	2.7	3.6	3.7	3.7
	3+08.39 [a]	2.7	3.6	3.7	3.8
	3+69.72	2.7	3.6	3.7	3.8
	4+15.89	2.4	3.3	3.5	3.5
	5+69.03	3.1	4.1	4.2	4.2
Average velocity magnitude (ft/s)	1+04.02	1.6	1.9	1.9	2.0
	1+86.48	1.9	2.5	2.5	2.6
	2+63.12	1.6	2.3	2.4	2.4
	3+08.39 [a]	1.6	2.2	2.2	2.3
	3+69.72	1.6	1.9	2.0	2.0
	4+15.89	1.5	2.2	2.3	2.3
	5+69.03	1.3	2.0	2.1	2.4
Average shear stress (lb/SF)	1+04.02	0.7	0.8	0.8	0.8
	1+86.48	1.0	1.4	1.4	1.5
	2+63.12	0.6	1.1	1.2	1.2
	3+08.39 [a]	0.6	1.0	1.0	1.1
	3+69.72	0.6	0.8	0.8	0.8
	4+15.89	0.6	1.1	1.2	1.2
	5+69.03	0.5	0.9	1.0	1.3

a. Cross section located at removed roadway embankment.

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Table 11: Natural-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main ch.	ROB [a]
1+04.02	1.3	1.9	0.8
1+86.48	1.1	2.5	0.7
2+63.12	0.9	2.3	0.7
3+08.39 [b]	0.9	2.2	0.8
3+69.72	0.6	1.9	0.6
4+15.89	0.7	2.2	0.8
5+69.03	0.8	2.0	1.4

a. ROB/LOB locations were approximated at the tops of banks

b. Cross section located at removed roadway embankment.

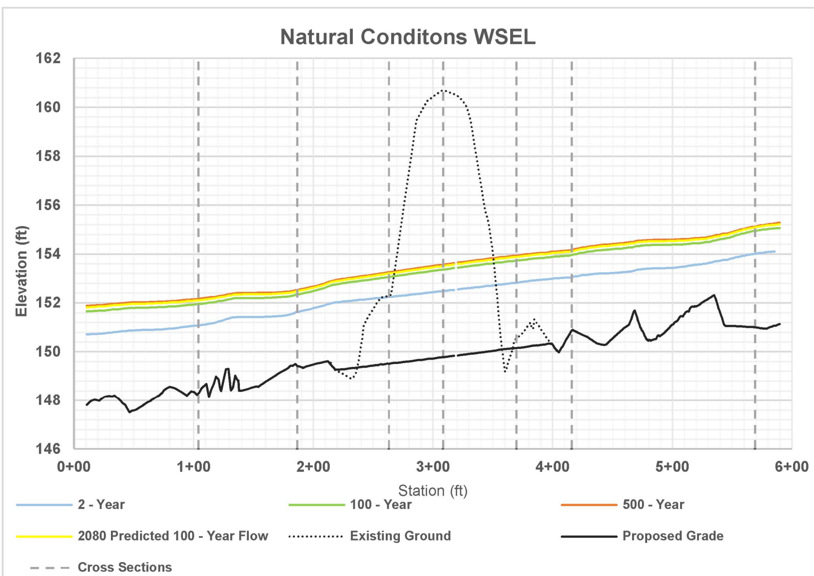

Figure 44: Natural-conditions water surface profiles

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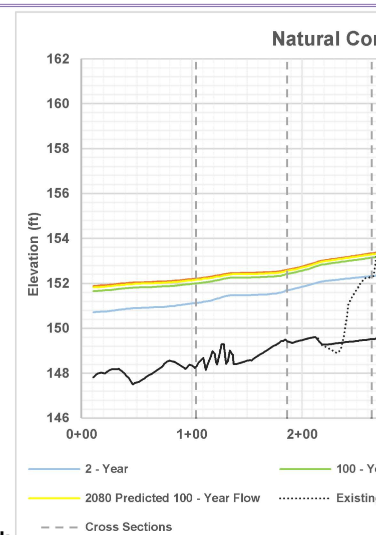

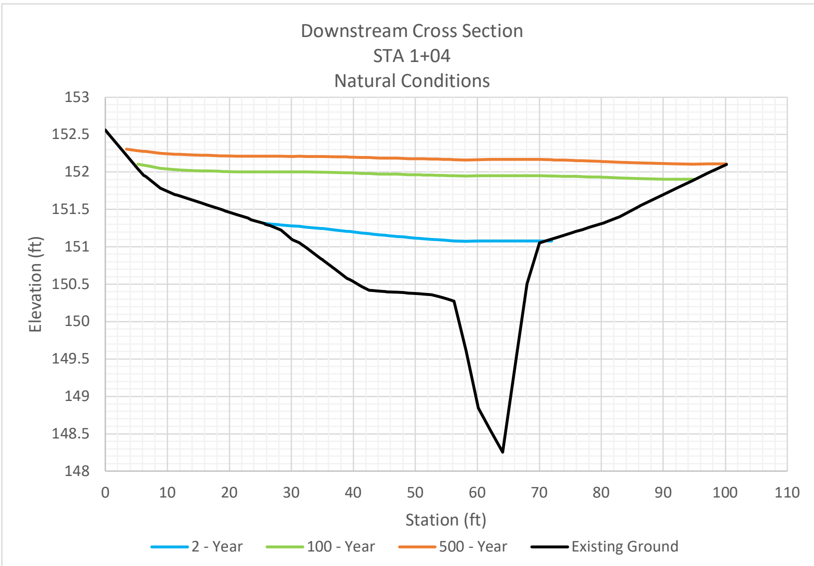

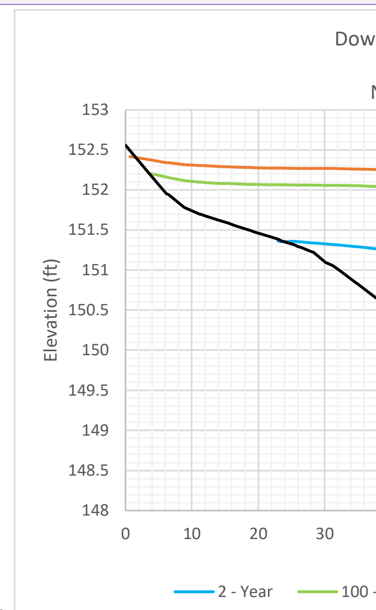

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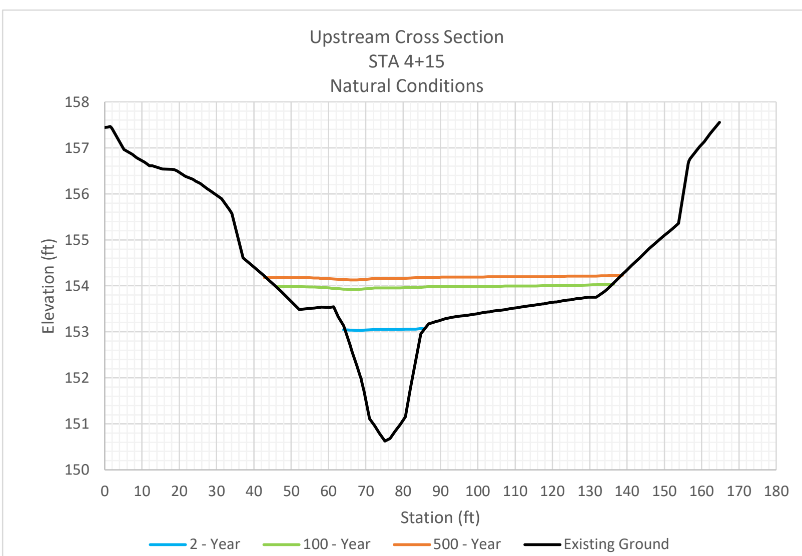
Figure 45: Typical downstream natural-conditions channel cross section (STA 1+04)



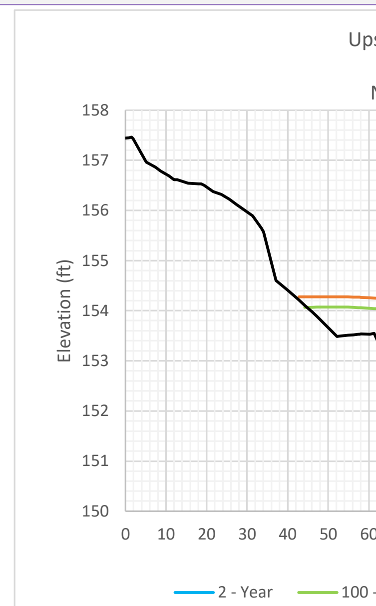


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Figure 46: Typical upstream natural-conditions channel cross section (STA 4+15)

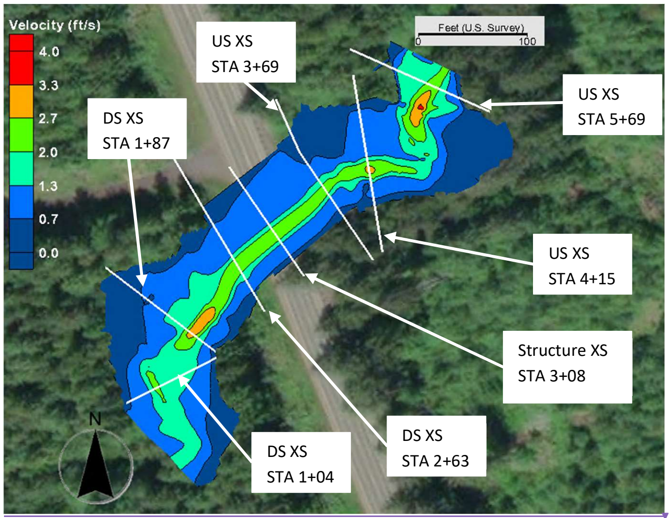


Figure 47: Natural-conditions 100-year velocity map with cross-section locations

4.4 Channel Design

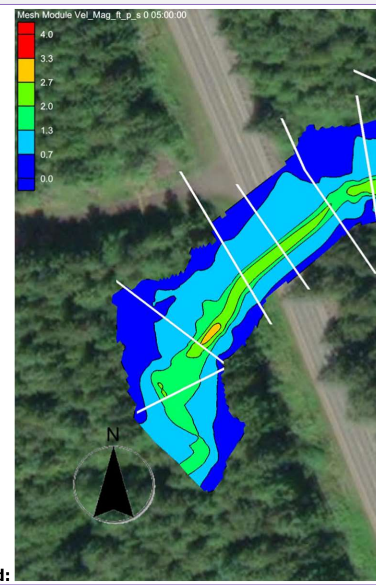
This section describes the development of the proposed channel cross-section and layout design.

4.4.1 *Floodplain Utilization Ratio*

The floodplain utilization ratio (FUR) is defined as the flood-prone width (FPW) divided by the BFW. The FPW is the water surface width at the 100-year flood. A ratio under 3.0 is considered a confined channel and above 3.0 is considered an unconfined channel. Because of the substantial backwater condition experienced under existing conditions, the FUR was computed using natural conditions (Table 12). Five measurement locations were selected as depicted in Figure 48. Using a BFW of 18 feet, these FPWs result in an average FUR of 4.8, with a slightly larger average in the downstream reach, which results in classifying the channel as 'unconfined'. Section 4.7.1 starts with this information in developing the structure design.

Table 12: Flood-prone widths and floodplain utilization ratio results

Parameter	Measurements (ft)					
	Downstream		Upstream			Average
	1+04	2+63	3+69	4+15	5+69	-
FPW (measured from 100-year top width of model)	89.6	92.8	91.4	90.4	69.9	86.8
Associated FUR	5.0	5.2	5.1	5.0	3.9	**4.8**
Average FUR (upstream and downstream)	**5.1**		**4.7**			

Deleted: 

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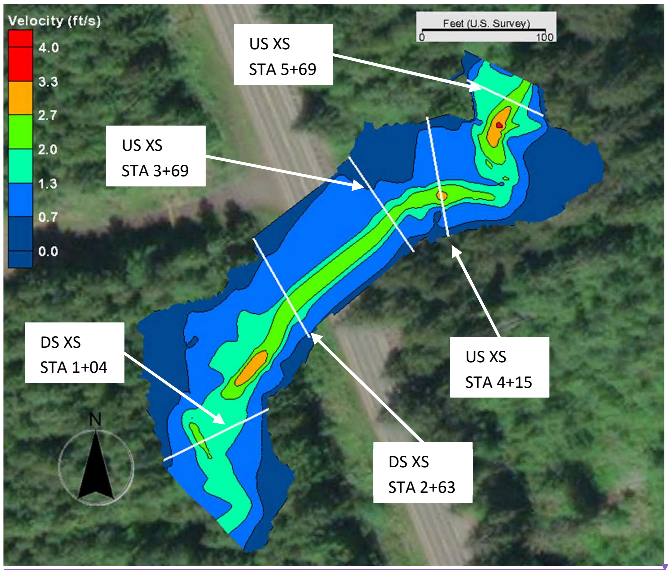

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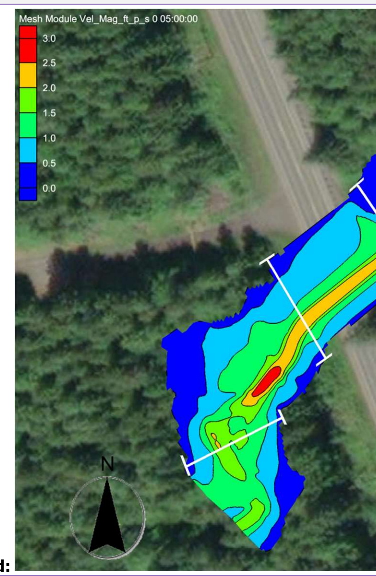

Figure 48: Locations of FPW measurements

4.4.2 *Channel Planform and Shape*

The WCDG prefers in a stream simulation design that the channel planform and cross-section shape mimic conditions within a reference reach (Barnard et al. 2013). The proposed channel cross-section shape accordingly emulates WSDOT's typical reference channel-based design (Figure 49), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. The bottom of the reference-based channel cross-section shape has a side slope of 10 horizontal (H):1 vertical (V) between the thalweg and bank toes, 2H:1V streambank slopes, and an overbank terrace at roughly a 50H:1V slope to create a channel similar to the observed existing channel shape. It is expected that the bottom shape will continue to adjust naturally during high water, where the proposed shape provides a reasonable starting point for subsequent channel shape evolution and bank stability will be provided via bioengineering design. Overall, the proposed design cross-section shape approximates reference reach conditions (Figure 50).

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Bioengineering methods can be implemented towards long term stability of the reference channel cross-section shape and planform outside the culvert. This is not necessarily applicable under replacement structures that are not long, high bridges, however, as is the case for this site where bank stabilizing vegetation typically will not grow and use of large woody material presents special constructability and maintenance problems. Except for very slow, low gradient channels, it is not possible to preserve a steep side slope without vegetation or specifying a particle size that is markedly larger than that typically specified for an alluvial, mobile streambed and is stable under all flows. For the project stream's gradient, side slope stability equations predict that while the native gravel substrate GSD may be just stable on a 2H:1V side slope at the 2-year flood peak, it will be mobilized and the cross-section shape will regrade at higher flood levels (cf. Appendix D). Indeed, this is a primary reason why the profiles of constructed stream simulation designs using gravel and cobble tend to wash out and flatten within the first winter season of high flows in many streams. However, as discussed in Section 5, the grain size distribution of the native substrate material is estimated to be sufficient to preclude complete flattening out of the streambed at this site. Constructed meander bars are accordingly also expected to remain stable.

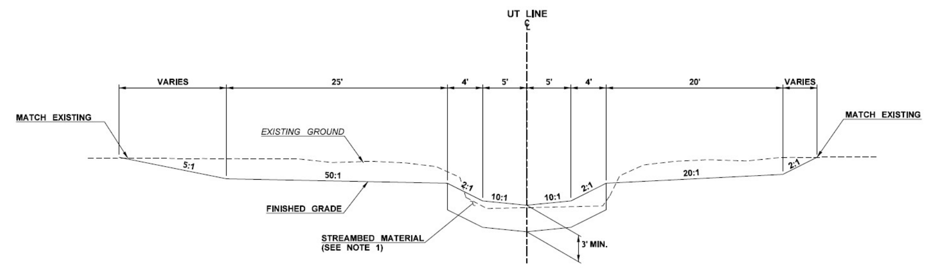

Figure 49: Reference channel-based design cross section for outside the culvert footprint.

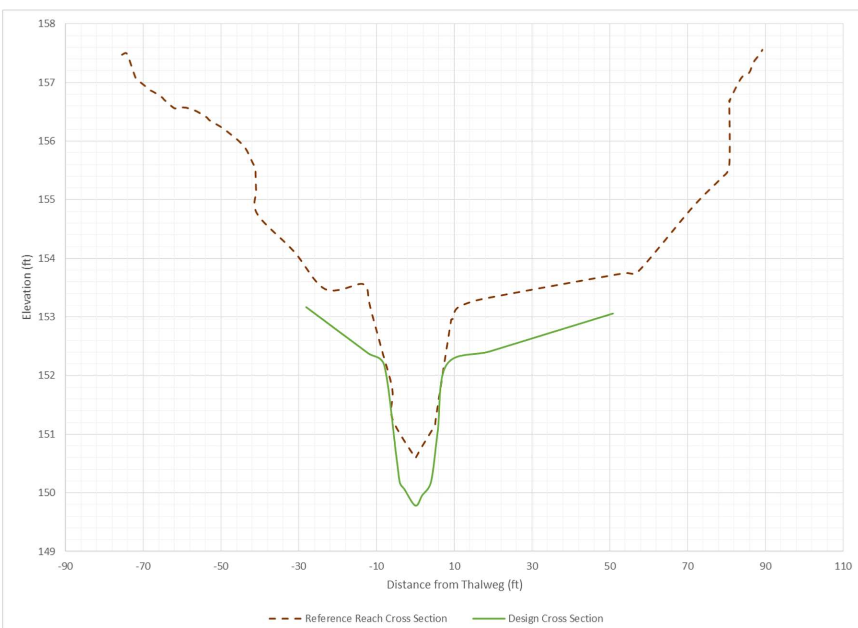

Figure 50: Comparison of design cross-section with a representative cross-section outside of the replacement structure footprint

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Outside of the replacement structure, the proposed channel cross-section profile generally follows WSDOT's typical reference channel-based design (Figure 49), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. The existing-conditions model results show that the 2-year flood event goes overbank in the existing channel conveys with overbank minimal expansion into the overbanks. The proposed channel shape consists of 10 horizontal (H):1 vertical (V) slopes between the toes and 2H:1V bank slopes fit within the design bankfull width, and floodplain benches with slopes ranging between 20H:1V to 50H:1V. The proposed design cross-section profile overall approximates the reference reach morphology (Figure 50).¶
As discussed above, however, the proposed design cross section within the structure will reflect the constraint posed by side slope stability of an unarmored, non-cohesive streambed, and the geomorphic observation that gravel supply rates to the culvert are expected to be lower than transport capacity. An over-steepened side slope with too small a substrate size distribution can be expected to regrade and flatten out during the first winter high flow(s) if a mobile bed is specified, and lose material to downstream that may then subsequently plug the channel there. For example, for the design stream slope of 0.007 and a streambed blend with a D_{50} = 1.2 inches, which is more than twice the typical gravel patch substrate D_{50} (see Table 4), . a maximum 10H:1V side slope is predicted to be required for stability during the 2080 100 year flood (Appendix D). . The 2H:1V side slope in the reference-based channel profile will accordingly not stay in place without a stabilizing influence such as can be provided by vegetation, or by a large sized substrate. A larger D_{50} = 4.2 inches is associated with a stable 2H:1V side slope, but constructing the channel within the culvert using only this size material will equate to designing a roughened channel that is fixed in place, and it is likely that the side slope may still erode and regrade over time as debris and wildlife pass through the culvert. .¶

The design goal for spacing of the bars should reflect a maximum head drop over a naturally formed riffle, rather than emulating a classic geomorphic pool-riffle spacing criterion, given the meander bars are intended to remain in place generally. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria for juvenile salmonids to accommodate upstream movements of other native fish species. For this site, a head drop of 3 inches between bar apices was selected based on professional judgment, where the drop is expected to be across a naturally formed riffle after the streambed is reworked by floods, assuming worst case regrading occurs such that the gradient of the streambed between bar apices becomes flatter.

4.4.3 *Channel Alignment*

The proposed perpendicular project alignment diverges from the existing alignment to increase the radius of curvature of the constructed bends upstream and downstream of the crossing. The project will include channel grading approximately 60 feet downstream of the channel outlet to roughly 14 feet upstream of the channel inlet to below the first existing grade control (see section 2.8.4).

The proposed channel alignment and grading extents are illustrated in design drawings provided in Appendix E.

4.4.4 *Channel Gradient*

The WCDG recommends that the proposed culvert bed gradient not be more than 25 percent steeper than the existing stream gradient upstream of the crossing (WCDG Equation 3.1). The proposed channel gradient is 0.6 percent and the reference reach gradient is 0.7 percent, resulting in a slope ratio of 0.9 which satisfies WCDG recommendations. This project is anticipated to have a low risk for long-term degradation or aggradation because of the uniformity of the slope at the watershed scale, as previously discussed in Section 2.8.4.

4.5 Design Methodology

The proposed fish passage design was developed using the 2013 *Water Crossing Design Guidelines* (Barnard et al. 2013) and the WSDOT *Hydraulics Manual* (WSDOT 2019). Using the guidance in these two documents, the unconfined bridge design method was determined to be an appropriate starting point at this crossing because the FUR was calculated to be greater than 3.0.

4.6 Future Conditions: Proposed 25-Foot Minimum Hydraulic Opening

The determination of the proposed minimum hydraulic opening width is described in section 4.7. A 25 feet wide opening was modeled as an open channel with an 18 ft BFW channel and floodplain, with vertical side walls. The resulting hydraulic predictions were used in the analyses described in section 4.4 to yield design parameters for freeboard and substrate sizing, and for guiding final design of a persistent cross-section profile within the culvert absent bank-stabilizing vegetation.

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As can be inferred from above, there is some flexibility in the design of the cross-section profile side slope, but this reflects the constraint posed by substrate size. We have found a 7H:1V side slope to generally work well in that it is associated with a passage lane for juvenile salmonids that is approximately 2 inches deep at a flow of 1 cfs, and only a slightly greater D_{50} (1.25 inches) than the stable streambed mix for a flat slope (1.2 inches) is required for stability during the 100-year flood peak. This side slope is not substantially greater than the bottom slope of the reference-based streambed channel fill and thus can be warped to join the outside constructed channel cross-section. ¶
The prismatic option is simpler to construct than a meandering thalweg, but can be associated with faster flows because flow resistance is provided only by grain size. The meandering option can include an additive flow resistance component in the form of alternating bars that dissipate some of the stream energy as bedforms, and can be implemented via the following proposed design considerations:¶
The alternating bars should be composed of . . generally immobile material. Material between and around the bars can be composed of smaller grain sizes, albeit not so small that the intervening material is washed out without replacement. Based on calculations in section 5 and Appendix D, the bars will be composed of 4 inch minus cobbles, and the surrounding streambed will be composed of a mix of 4 inch cobble and streambed sediment following WSDOT's standard specifications 9-03.11(2) and 9-03.11(1), respectively.¶
Spacing of the bars should reflect a maximum head drop design goal rather than emulation of a classic geomorphic pool-riffle spacing criterion, given the bars are to be effectively stable. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria. For this site, a ... [5]

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The proposed perpendicular project alignment diverges from the existing alignment to increase the radius of curvature of the constructed bends upstream and downstream of the crossing. The project will include channel grading approximately 60 feet

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Proposed-conditions hydraulic results are summarized for the upstream and downstream cross sections as well as the cross section within the proposed crossing in Table 13. Average velocities across the main channel, LOB, and ROB of each cross section for the 100-year flow are shown in Table 14. The larger proposed structure reduced WSELs upstream and does not cause backwater upstream of the structure (Figure 51). The 2080 projected 100-year flow WSEL is nearly equal to the 500-year flow. The 100-year WSEL at the upstream cross section (STA 3+69) decreased by 3.8 feet from existing conditions. Also, there is no overtopping of U.S. 101 under proposed conditions and all flow is conveyed through the proposed opening. A cross section showing WSEL in the proposed structure is shown in Figure 52. Maps of the predicted velocity fields for the present day and 2080 100-year flood peaks are depicted in Figures 53 and 54. Velocities upstream were predicted to increase substantially from existing conditions because of the elimination of backwater upstream. Velocities downstream are similar, with the exception of the realigned portion of the channel, which provides a straighter and more uniform channel reach that allows for slightly more substantial (0.19 ft/s) increases to velocities at low flow conditions.

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Upstream channel velocities vary from 1.87 to 2.72.5 ft/s, and the downstream proposed-conditions velocities vary from 1.6 to 3.12.9 ft/s.

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Table 13: Hydraulic results for proposed conditions within main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	2080 predicted 100-year	500-year
Average WSEL (ft)	1+04.02	151.1	152.0	152.1	152.2
	1+86.48	151.6	152.4	152.5	152.5
	2+63.12	152.1	152.9	153.1	153.1
	3+08.39 [a]	152.2	153.0	153.1	153.2
	3+69.72	152.4	153.3	153.5	153.6
	4+15.89	152.8	153.8	153.9	154.0
	5+69.03	154.0	154.9	155.1	155.1
Maximum water depth (ft)	1+04.02	2.8	3.7	3.9	3.9
	1+86.48	2.2	3.0	3.1	3.1
	2+63.12	2.5	3.3	3.5	3.5
	3+08.39 [a]	2.1	2.9	3.0	3.1
	3+69.72	2.3	3.2	3.4	3.4
	4+15.89	2.2	3.1	3.3	3.4
	5+69.03	3.1	4.0	4.2	4.2
Average velocity magnitude (ft/s)	1+04.02	1.6	1.9	1.9	2.0
	1+86.48	1.9	2.4	2.5	2.5
	2+63.12	1.3	2.3	2.5	2.6
	3+08.39 [a]	1.8	3.0	3.3	3.4
	3+69.72	1.9	2.6	2.7	2.7
	4+15.89	1.7	2.5	2.6	2.6
	5+69.03	1.3	2.0	2.1	2.1
Average shear stress (lb/SF)	1+04.02	0.7	0.8	0.8	0.8
	1+86.48	1.0	1.4	1.4	1.4
	2+63.12	0.3	0.7	0.8	0.9
	3+08.39 [a]	0.1	0.3	0.4	0.4
	3+69.72	1.0	1.5	1.6	1.6
	4+15.89	0.9	1.5	1.5	1.6
	5+69.03	0.5	0.9	1.0	1.0

[a] Cross section located within proposed structure

Table 14: Proposed-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main ch.	ROB [a]
1+04.02	1.3	1.9	0.8
1+86.48	1.0	2.4	0.7
2+63.12	1.0	2.3	0.5
3+08.39 [b]	2.3	3.0	2.4
3+69.72	0.7	2.6	0.6
4+15.89	0.7	2.5	0.8
5+69.03	0.9	2.0	1.4

a. ROB/LOB locations were approximated at the tops of banks from inspecting the surface and 2-year top width.
b. Cross section located at proposed structure.

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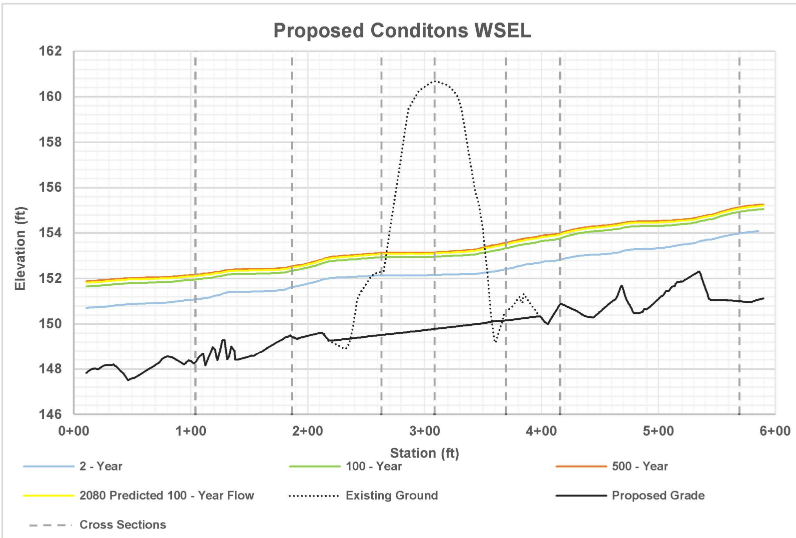

Figure 51: Proposed-conditions water surface profiles

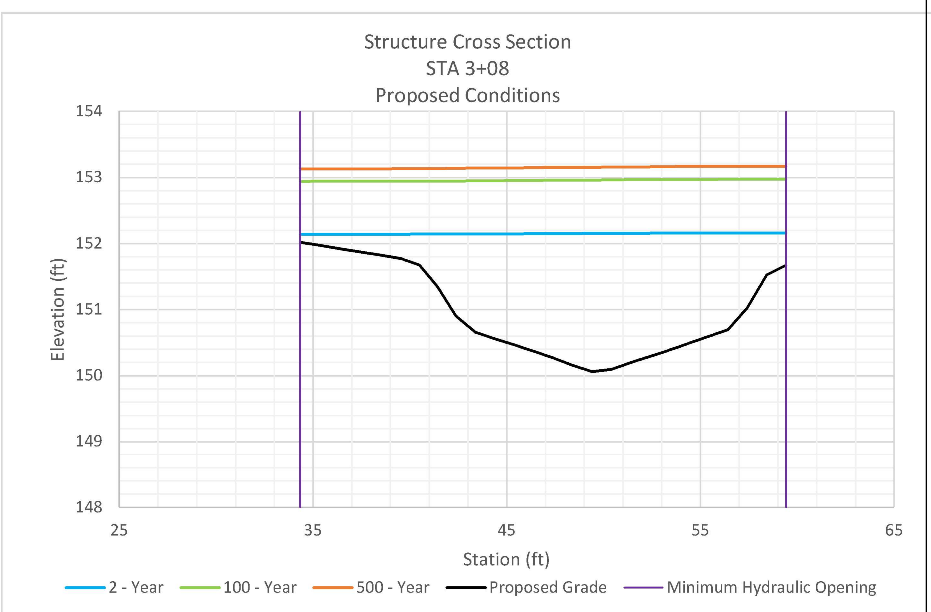

Figure 52: Section through proposed structure (STA 3+08)

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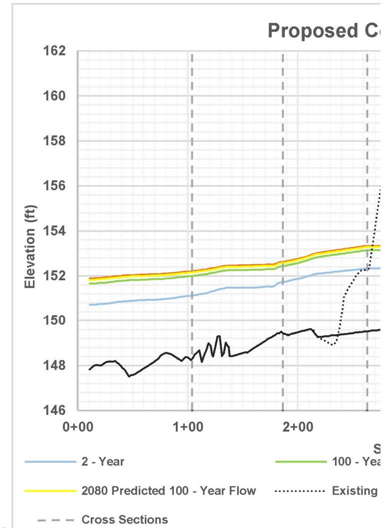

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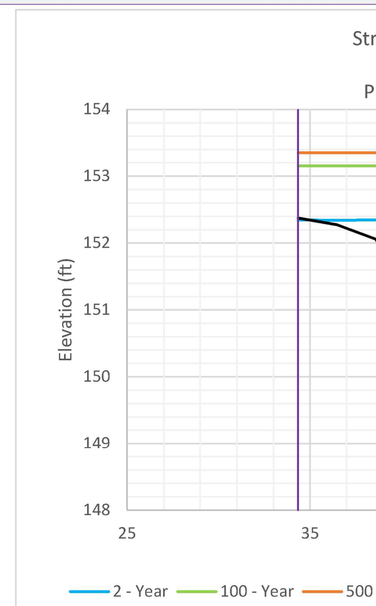

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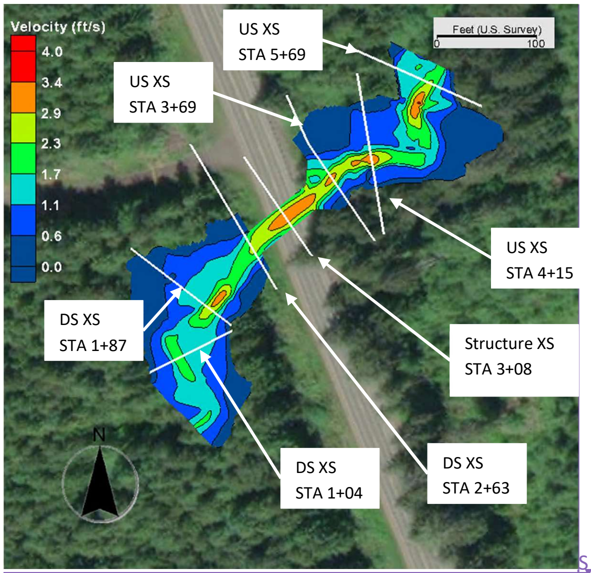

Figure 533: Proposed-conditions present day 100-year velocity map

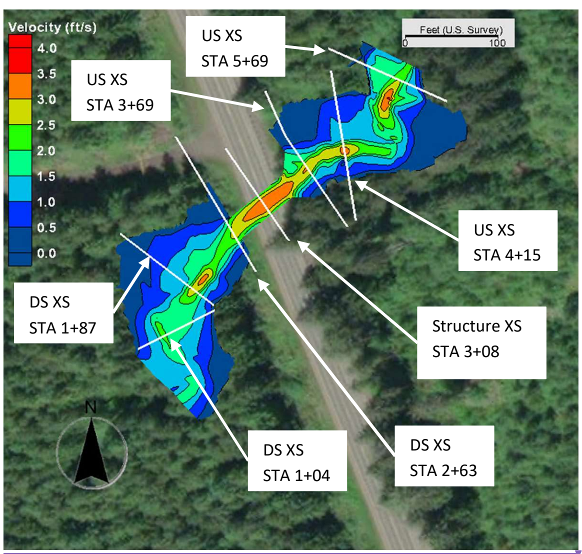

Figure 544: Proposed-conditions 2080 predicted 100-year velocity map

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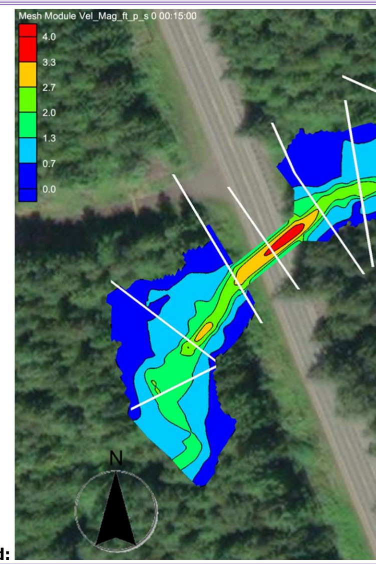

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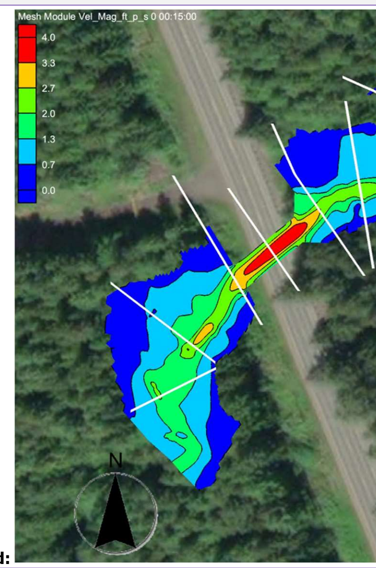

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4.7 Water Crossing Design

Water crossing design parameters include structure type, minimum hydraulic opening width and length, and freeboard requirements.

4.7.1 *Structure Type*

A structure type has not been resolved at present and will be determined at later project phases.

4.7.2 *Minimum Hydraulic Opening Width and Length*

The hydraulic opening is defined as the width perpendicular to the creek beneath the proposed structure that is necessary to convey the design flow and allow for natural geomorphic processes. The hydraulic opening assumes vertical walls at the edge of the minimum hydraulic opening width unless otherwise specified. The starting point for determining the design width of all WSDOT structures is Equation 3.2 of the WCDG (Barnard et al. 2013), rounded up to the nearest whole foot. For this crossing, a minimum hydraulic opening of 24 feet was determined to be the minimum starting point based on a BFW of 18 feet determined by field measurements as outlined in Section 2.8.2. As noted there, this value is generally wider than would be expected based on drainage area and BFW comparisons with other streams, and thus is likely to be a conservative value for flood conveyance. To accommodate wildlife connectivity, the minimum hydraulic opening was increased to 25 feet per direction of WSDOT.

The present day and projected 2080 100-year flood magnitudes were evaluated for the proposed and reference conditions to evaluate the velocity ratio. The ratio provides a measure of the extent to which flow is accelerated inside the structure by comparing the main channel velocity through the proposed structure to that of the unrestricted stream channel. The proposed 25-ft structure yields a velocity ratio of 1.1 at the 100-yr event. This ratio meets the required criteria and indicates that there is minor acceleration within the proposed structure as compared to the unrestricted floodplain, but this minor acceleration is insufficient to result in scouring or over coarsening of the culvert bed material (see Section**Error! Reference source not found.**). Hydraulic model results also indicate low velocity zones formed by the meander bars within the culvert, which would provide refuge for fish. The proposed 25-ft structure is sufficiently wide to allow for aquatic organism passage and the natural geomorphic processes of the stream.

Table 15: Velocity Ratio for Proposed 25-ft Structure

Simulation	Hydraulic Opening Width (ft)	Reference 100-Year Velocity (ft/s)	Proposed 100-Year Velocity (ft/s)	Velocity Ratio
100-year	25	2.4	2.7	1.1
2080 100-year	25	2.5	3.0	1.2

The proposed length of the structure is approximately 80 feet, but will be confirmed pending further roadway design.

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4.7.3 ***Freeboard***

Freeboard is necessary to allow the free passage of debris expected to be encountered. The WCDG generally suggests a minimum 3-feet clearance above the 100-year WSEL for streams with a BFW greater than 15 feet to adequately pass debris (Barnard et al. 2013), and WSDOT applies this criterion to structures 20 feet and wider. WSDOT furthermore desires a minimum vertical clearance between the culvert soffit and the streambed thalweg for maintenance equal to 6 feet where possible. WSDOT is incorporating climate resilience in freeboard, where practicable, and so freeboard was evaluated at the projected 2080 100-year WSEL. The hydraulic modeling indicates that the maintenance-based goal will exceed the clearance required to meet the 3 feet hydraulic-based criterion associated with the proposed design when constructed. The evaluation of long-term aggradation and degradation presented in Section 2.8.4 indicated that there is a low likelihood of aggradation at the site, where additional freeboard to accommodate future aggradation does not appear warranted at this site.

The resulting parameters governing freeboard are summarized for the 25 feet wide structure in Table 16, and accommodate the future climate change scenario by evaluating for the 2080 100-year flood scenario.

Table 16: Parameters relevant to freeboard specification for proposed replacement structure

Parameter	2080 100-Year Coincident Flood Predictions	
	At Inlet	At Outlet
Thalweg elevation (ft)	150.16	149.61
Maximum WSEL (ft)	153.33	153.07
Minimum low chord elevation to provide 3 feet of freeboard (ft)	156.33	156.07
Minimum low chord elevation to provide 6 feet maintenance access (ft)	156.16	155.61
Recommended low chord elevation, without future aggradation (ft)	156.33	156.07
Recommended low chord elevation, with future aggradation (ft)	156.33	156.07

There may be additional freeboard considerations because this crossing has other wildlife considerations; see Section 2.6.

4.7.3.1 Past Maintenance Records

WSDOT has indicated there have been no maintenance problems at this crossing .

4.7.3.2 Wood and Sediment Supply

The project stream flows through a heavily wooded basin with a high potential for recruitment. However, the lower gradient wetlands upstream of the crossing are likely to trap any large mobile wood. As described in section 2.8.6, mobile wood pieces in the stream appear to be smaller than 5 inches in diameter and around 9 feet in length, and thus would be expected to clear easily under the proposed 24 feet wide structure with more than 3 feet of freeboard during the 100-year flood now and in the future.

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4.7.3.3 Flooding

Though FEMA has not conducted a Special Flood Hazard Area analysis at this site (Section 2.3), the roadway of U.S. 101 does overtop under existing conditions for the 500-year flow event.

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4.7.3.4 Future Corridor Plans

There are currently no long-term plans to improve U.S. 101 through this corridor.

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4.7.3.5 Impacts

It is not anticipated that the road level will be raised to accommodate the proposed minimum hydraulic opening. A final decision will be made at a later design phase.

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4.7.3.6 Impacts to Fish Life and Habitat

At this time and with the current level of information with regard to wildlife in the area, the proposed freeboard of 3 feet based on hydraulic considerations is not expected to result in substantial impacts to fish life and habitat. In addition, the structure height will likely be increased to accommodate a wildlife crossing.

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5 Streambed Design

The streambed design considered the local characteristic grain size distribution (GSD) of gravel collected in the sieve sample, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two GSDs were developed, one for the streambed mix, and the second for a cobble armor surface on the proposed meander bars within the replacement structure. In addition, large wood material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.

5.1 Bed Material

Where neither of the other two alternative approaches identified in Section 1.0 are indicated for implementation, the injunction requires that the design follow the stream simulation methodology as described in the WAC and WCDG (Barnard et al. 2013). WAC 220-660-190 stipulates that "The median particle size of sediment placed inside the stream-simulation culvert must be approximately twenty percent of the median particle size found in a reference reach of the same stream. The department [WDFW] may approve exceptions if the proposed alternative sediment is appropriate for the circumstances." The reference reach of this stream is primarily composed of fines, with some isolated gravel patches. The proposed streambed gradation is more consistent with the isolated gravel sample as discussed in Section 2.8.3, as it is not practical to construct a culvert bed consisting completely of fines. However, WSDOT's streambed sediment specification, which has a larger D_{50}, represents the smallest constructible bed material for the project. Therefore, the proposed design is based on WSDOT's standard specifications for streambed sediment and cobble, as described below.

The evaluation of streambed instability risk focused on evaluating the stability of the D_{84} size at the 2- and 100-year flood peaks. WSDOT's standard worksheet for evaluating the stability of the D_{84} size using the modified Shields stress method (USFS 2008) is presented in Appendix D. It is based on assuming intermittent transport generally occurs when the dimensionless ("Shields") shear stress is less than 0.03 in value, and partial mobility falls with the range 0.03-0.06 (Lisle et al. 2000; Wilcock et al. 1996; Pasternack and Brown 2013). To emulate a partially adjustable streambed for this design, the critical dimensionless shear stress for the modified Shields stress method was set to 0.045, using estimates of shear stress.

The SRH2D model outputs an estimate of shear stress, but the result is based on a 2-D vector adaptation of the uniform flow, wide channel 1-D approximation, and accordingly is a significant over-estimate compared with that derived from velocity profiles (Wilcock 1996; Pasternack et al. 2006; DeVries et al. 2014). Pasternack and Brown (2013) determined that the type of equation used more closely matches the velocity profile-derived estimate when the velocity is evaluated near the bed. However, SRH2D calculates a mean column velocity, but that can be used to estimate near bed shear velocity and thus shear stress. Two different velocity relations based on the rough form of the law of the wall were evaluated accordingly, and they gave comparable order of magnitude predictions of shear stress

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Deleted: WSDOT has decided that exceptions should be avoided where possible. In general, what this means is that the streambed substrate grain size distribution is required to have a D_{50} within +/- 20 percent of the native reference substrate. . This requirement is not strictly possible to meet at this site, because the reference reach substrate consists primarily of fine material that would not be expected to remain stable if placed within the culvert. . There are isolated patches of gravel, so an exception is recommended for this site where the streambed design is instead based on the reference gravel patch grain size distribution with an assessment of risks associated with potential streambed instability. Relevant calculations are presented in Appendix D and their implications to the design are summarized below.

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(Richards 1982; Pasternack and Brown 2013). The larger of the two estimates was used to evaluate the mobility of the D_{84} size following the modified Shields stress method. WSDOT's worksheet in Appendix D predicts that the native gravel D_{84} size should be generally stable. This result is consistent with field observations where the gravel deposit from which the bulk sieve sample was collected was heavily embedded with fine sand and silt. The worksheet was used to then specify the GSD based on the stable D_{84} value and WSDOT's standard specifications for streambed sediment and cobbles.

In addition, the analyses in Appendix D indicate that the proposed gradation should be stable on a side slope that is intermediate to 2H:1V and a flat cross-section profile, which should ensure the general persistence of meander bars within the replacement structure, and concentrate flows over the lower flow range within a narrower notch that provide depths for upstream passage. A 7H:1V side slope was selected as a design goal because it is not substantially different from the 10H:1V design bottom slope of the reference cross-section depicted in Figure 49. WSDOT's standard specification 9-03.11(1) was determined to be stable on this side slope at the 100-year flood peak based on stability equations in Mooney et al. (2007). The stability analysis results imply that the meander bar GSD does not need to be coarser than the proposed streambed mix, but the proposed meander bar GSD has been adjusted to include 4" cobbles in order to provide a safety factor to ensre the proposed cross section does not flatten out to a plane bed and maintains a low flow passage lane.

The geomorphic reach conditions are such that the supply rate of native gravel from upstream would be insufficient to replace gravel mobilized from the culvert streambed over the long term. Therefore, the largely immobile proposed streambed design consisting of 100% streamed sediment is appropriate for this site (Table 17). The proposed bed material for this stream consists of 100% streambed sediment using WSDOT's standard specification 9-03.11(1). The proposed meander bars consist of 80% streambed sediment (9-03.11(1)) and 20% 4-inch cobbles (9-03.11(2)).

Because actual mixes noted as meeting WSDOT specifications at pit sources can be highly variable in their composition, the streambed mix GSD should be verified by sieving at the source and adjusted as needed to reflect materials that are actually available at the time of construction.

Table 17: Proposed streambed material

Sediment size	Observed Diameter (in)	Streambed Design Diameter (in)	Alternating Bar Design Diameter (in)
D_{16}	0.1	0.1	0.1
D_{50}	0.5	0.6	0.8
D_{84}	1.9	1.7	2.2
D_{90}	2.3	1.9	2.4
D_{MAX}	3.2	2.5	4.0

5.2 Channel Complexity

To mimic the natural riverine environment and promote the formation of habitat, the design incorporated placement of key LWM pieces within and across the channel and floodplain. Placement will

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Following the above approach, the critical Shields stress = 0.045 criterion corresponds approximately to a critical D_{50} = 0.25 inches at the 2-year flood, and 0.3 inches at the 2080 100-year flood. . Correspondingly, a streambed mix emulating the native gra ... [15]
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generally mimic tree fall that is common throughout the reach upstream of the crossing, and embedded wood pieces in the reach upstream and downstream to reflect characteristic geomorphic processes. Complexity is also provided by the alternating bar layout proposed in Section 4.4.

5.2.1 *Design Concept*

The total number of key pieces was determined in consideration of criteria presented in Fox and Bolton (2007) and Chapter 10 of the *Hydraulics Manual* (WSDOT 2019), in which WSDOT's recommended key piece density for the project site is 3.4 key pieces and 39.48 cubic yards of volume per 100 feet of channel. A key piece is defined as having a minimum volume of 3.275 cubic yards based on bankfull width (Appendix H), which corresponds roughly to a 30 feet long log that has a diameter at breast height (DBH) of 24 inches. WSDOT has established a design goal for this project where the Fox and Bolton (2007) criteria are to be calculated for the total regrade reach length including the culvert, but the pieces of wood are to be distributed outside of the culvert. For the proposed total regrade length of 150 feet, the design criteria for this reach are five key pieces with a total LWM volume of 59.2 cubic yards (Appendix H). In small streams, the volume criterion may not always be practically achieved without completely filling the channel and placing a sizeable amount of wood outside of the 2 year flood extent, where smaller diameter logs can achieve the same biological and geomorphic functions. In this design, the primary goal was to exceed the density criterion to get closer to or even meet the volume criterion, while not overloading the stream channel outside of the culvert. Where feasible, wood can be added outside of the regrade extent with the condition that heavy equipment not disturb the channel and floodplain significantly.

A conceptual LWM layout has been developed for the project reach involving a mix of embedded and loose logs with rootwads (Figure 55). The conceptual layout proposes 21 key pieces in an approximately 150-foot-long project reach (including the structure length), which greatly exceeds the number criterion for both key and non-key LWM in order to increase the volume and get that closer to the ideal target (Appendix H). In addition, this increased number is intended to maintain slower velocities during floods downstream of the crossing, similar to existing conditions, as well as reduce erosion potential at the hardpan grade control upstream. There is space for this number of pieces. In consideration of providing the contractor with some flexibility in sourcing, only five of these pieces will have DBH equal to or greater than 24 inches, the rest will be within the 15- to 20-inch DBH range, sizes that are comparable to other pieces of wood at the site. This increased number of variable sized pieces in turn facilitates getting closer to the net volume target (Appendix H). The mobility and stabilization of LWM will be analyzed in later phases of design. The design involves two log types:

- Eight (8) embedded logs (Type 1) with rootwads to provide habitat and stabilize the floodplain above and below the culvert; the logs are intended to be fixed in place within the excavated floodplain upstream and downstream of the replacement structure to reduce potential for entrainment and erosion of the floodplain outside of the structure. The rootwad will be placed in the low flow channel with a preformed scour hole around it, and the butt end will be buried to sufficient length and depth that additional anchoring is not needed.
- Thirteen (13) loose, 30+ feet long logs with rootwads, and to the extent possible, with intact branches. Two will be placed entirely in the channel (Type 2), eight will be placed with rootwad

in the channel and tip on the floodplain/adjacent slope (Type 3), and three will span the bankfull channel to promote scouring underneath (Type 4). The type 3 and 4 designs will involve self-ballasting and interlocking with existing trees and placed embedded logs for stability. The type 2 log will be kept in place by other logs on top, and wedging between streambanks.

The LWM pieces will be placed so they provide cover habitat features for juvenile salmonids during winter months, including refuge habitat under high flow conditions. Wood stability and the design of anchoring will be assessed at the Final Hydraulic Design (FHD) level. Key pieces will be designed to be anchored by either suitable embedment length/depth, or interlocking with existing trees. Smaller pieces would need to be placed loose as directed work, or designed to be embedded in the banks, integrated with the installation of key pieces.

Risk of fish stranding is possible in scour pools around rootwads because the stream was observed to go dry during the summer of 2021. Accordingly, scour pool excavation around rootwads is not included in the design for this site.

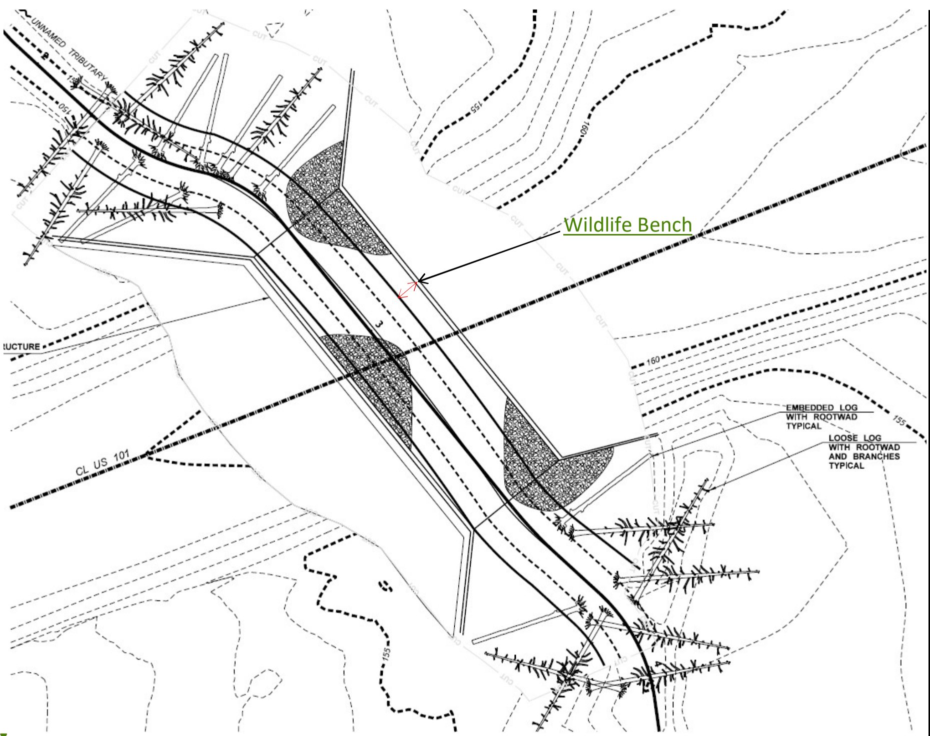

Figure 55: Conceptual layout of LWM and alternating bars for habitat complexity. Minimum 5 feet wide bench for wildlife connectivity is also shown.

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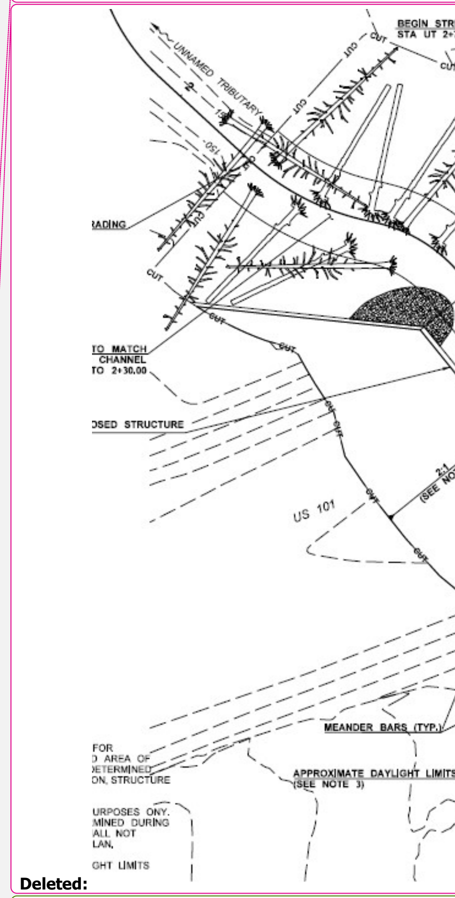

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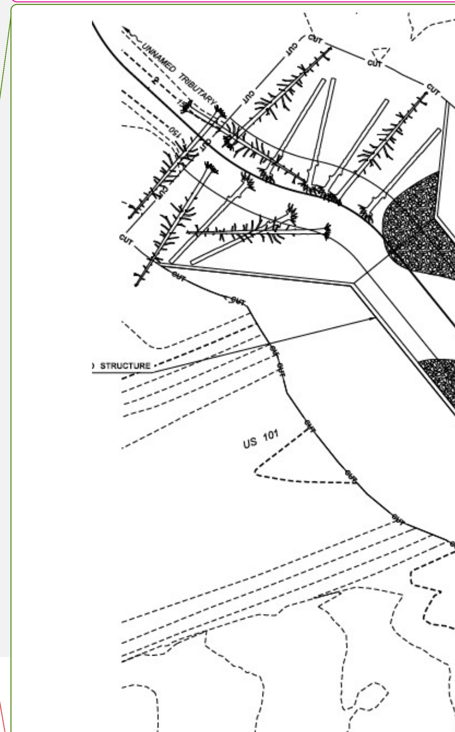

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6 Floodplain Changes

No FEMA flood hazard analysis was performed at this location (Section 2.3). The pre-project and expected post-project conditions were evaluated to determine whether there would be a change in WSEL and floodplain storage.

6.1 Floodplain Storage

Floodplain storage is anticipated to be significantly impacted by the proposed structure. The installation of a larger hydraulic opening will reduce the amount of backwater and associated peak flow attenuation that was being provided by the smaller, existing culvert. A comparison of pre- and post-project peak flow events was not quantified as the models were run with a steady flow rate specified at the upstream boundary of the model. U.S. 101 will no longer be overtopped during the 500-year flow event after installation of the proposed structure and, as a result, secondary flow from the project stream will no longer enter road drainage on the east side of U.S. 101. All flow will remain with the channel. There are no anticipated risks to existing infrastructure.

6.2 Water Surface Elevations

Installation of the proposed structure would eliminate the backwater impacts just upstream of the existing culvert, resulting in a reduction in WSEL upstream. The WSEL is reduced by as much as 3.8 feet at the inlet of the existing culvert at the 100-year event, as shown in Figures 56 and 57. Figure 57 shows a significant decrease in backwater with the proposed structure alignment, opening, and grading, during the peak 100-year event

Immediately downstream of the culvert, channel regrading for proposed conditions causes several, highly localized increases in WSEL of less than 0.1 foot. These are located entirely within the graded reach, likely because of changes such as filling in scour holes or reducing high points that serve as hydraulic control elements. Past the extent of the proposed grading, there is no change in water surface elevation from the existing to proposed conditions.

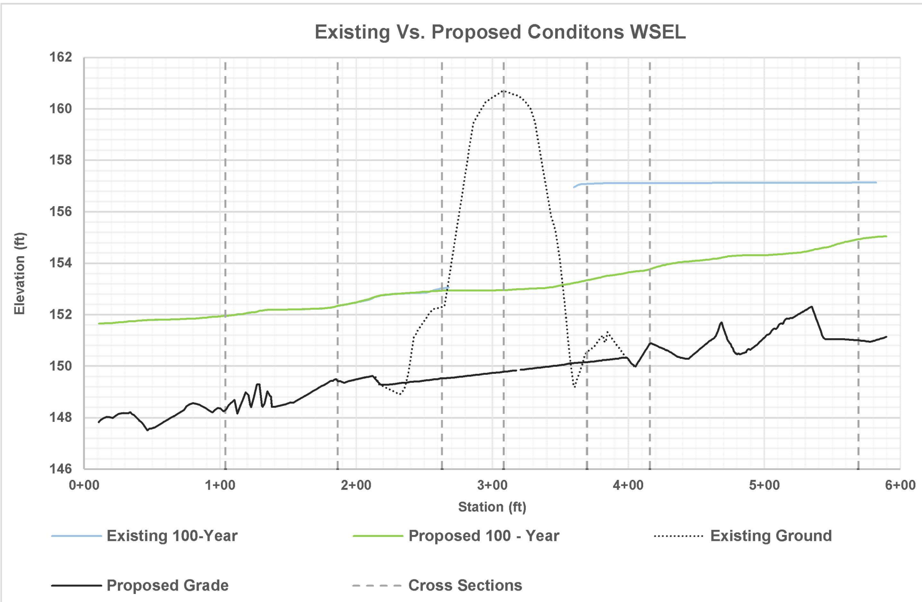
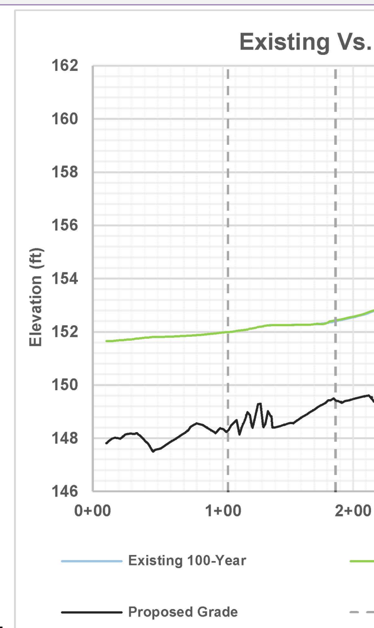


Figure 56: Existing and proposed 100-year water surface profile comparison



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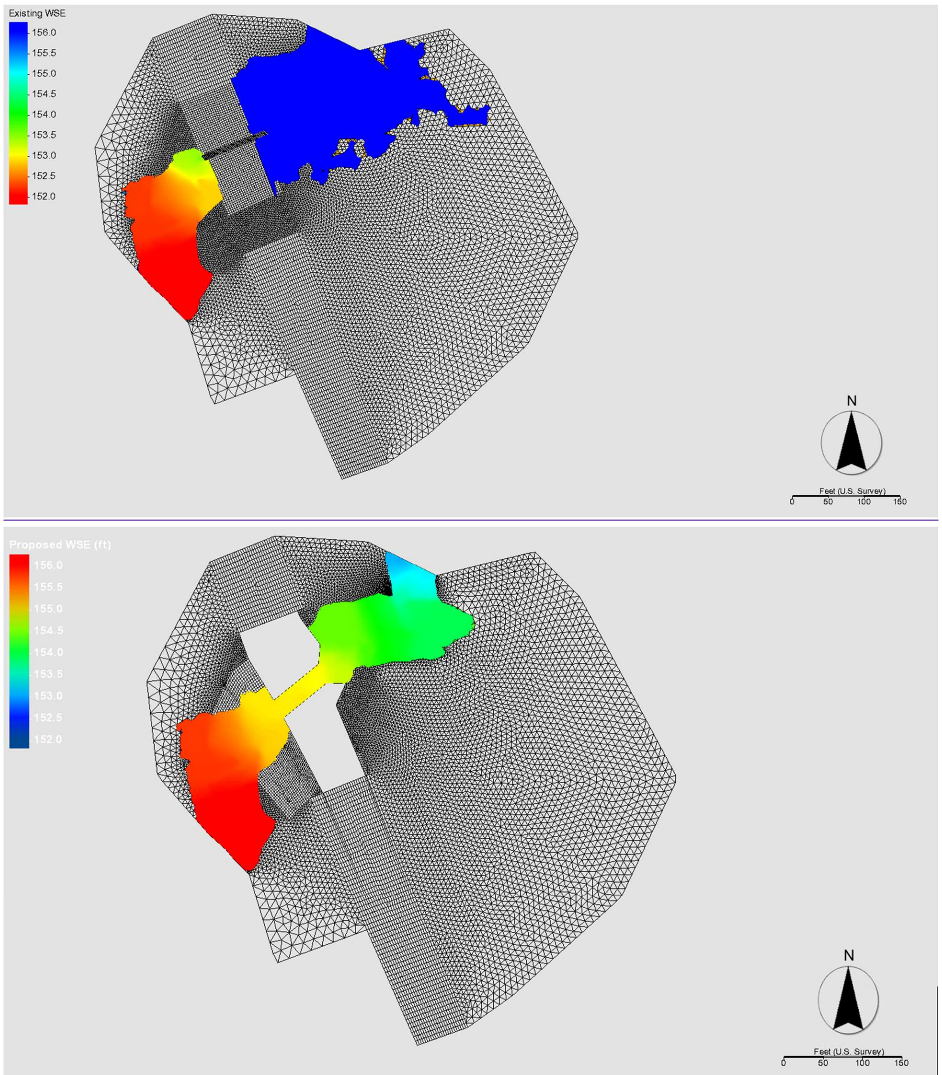

Figure 577: 100-year WSEL change

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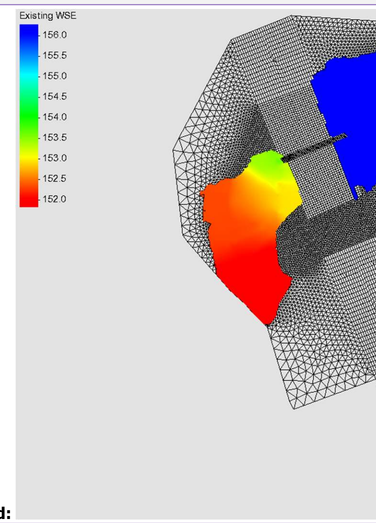

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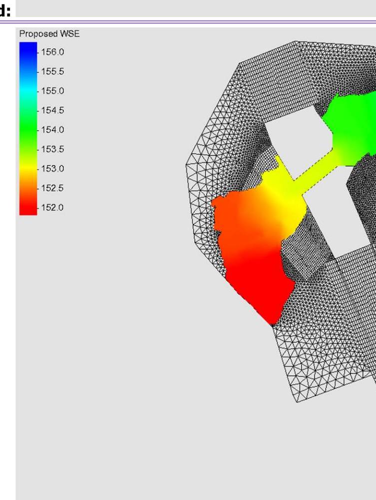

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7 Climate Resilience

WSDOT recognizes climate resilience as a component of the integrity of its structures and approaches the design of bridges and buried structures through a risk-based assessment. For this site, the largest climate change risk to the structure's performance will be from flow increases. The goal of fish passage projects is to maintain natural channel processes through the life of the structure and maintain passability for all expected life stages and species in a system. At a minimum, climate change is addressed in all bridge, buried structure, and fish passage projects by providing a design in which the foundations or bottoms are not exposed during the 500-year flow event due to long-term degradation or scour. WSDOT also completes a hydraulic model for all water crossings on fish-bearing streams, regardless of design methodology, to ensure that the new structure is appropriately sized. If the velocities through the structure differ greatly from those found elsewhere in the reach, the structure width may be increased above what is required by Equation 3.2 in the WCDG.

General climate change predictions for the broader region are for increased rainfall intensity during winter months, with the caveat that there is great spatial variability in the projections that may preclude downscaling to the project site drainage area, which is relatively small (WSDOT 2011). The project site crossing has been evaluated and determined to be a low risk site based on the Climate Impacts Vulnerability Assessment maps (Figure 58). Based on the determination of this location being a low risk site, no additional climate change design modifications were made. The new structures were designed so their foundations do not become exposed during the 500-year flow event. Also, hydraulic modeling indicated that the flow through the replacement culvert is not predicted to become pressurized (i.e., no freeboard) during the 500-year event.

7.1 Climate Resilience Tools

WSDOT also evaluates crossings using the mean percent change in 100-year flood flows from the WDFW Future Projections for Climate-Adapted Culvert Design program. All sites consider the percent increase throughout the design of the structure associated with the 2080 scenario. Appendix I contains the information received from WDFW for this site.

7.2 Hydrology

For each design WSDOT uses the best available science for assessing site hydrology. The predicted flows are analyzed in the hydraulic model and compared to field and survey indicators, maintenance history, and any other available information. Hydraulic engineering judgment is used to compare model results to system characteristics; if there is significant variation, then the hydrology is reevaluated to determine whether adjustments need to be made, including adding standard error to the regression equation, basin changes in size or use, etc.

In addition to using the best available science for current site hydrology, WSDOT is evaluating the structure at the 2080 predicted 100-year flow event to check for climate resilience. The design flow for the crossing is 145 cfs at the 100-year storm event. The projected increase for the 2080 flow rate is 16.8 percent, yielding a projected 2080 flow rate of 169 cfs.

7.3 Climate Resilience Summary

A minimum hydraulic opening of 24 feet allows for the channel to behave similarly through the structure as it does in the adjacent reaches under the projected 2080 100-year flow event. This will help to ensure that the structure is resilient to climate change and the system is allowed to function naturally, including the passage of sediment, debris, and water in the future.

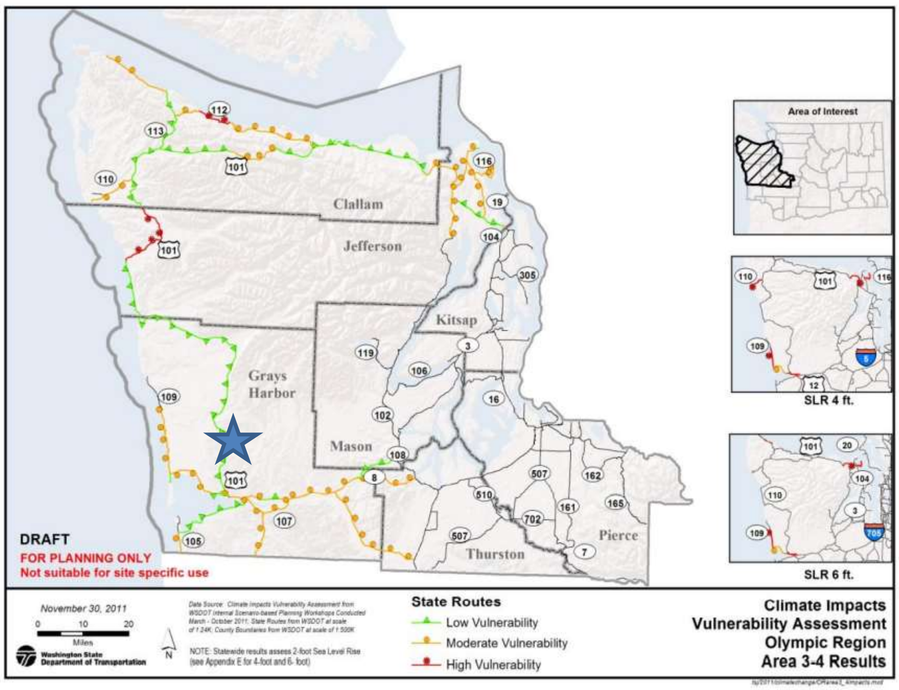

Figure 58: Climate impacts vulnerability assessment of Olympic Region areas 3 and 4 (source: WSDOT 2011). Site location is indicated by star

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8 Scour Analysis

Total scour will be computed during later phases of the project using the 100-year, 500-year, and projected 2080 100-year flow events. The structure will be designed to account for the potential scour at the projected 2080 100-year flow events. For this phase of the project, the risk for lateral migration and potential for degradation are evaluated on a conceptual level. This information is considered preliminary and is not to be taken as a final recommendation in either case.

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8.1 Lateral Migration

Channel migration was assessed by using historical imagery and modeling results. The historical aerial imagery gives little information on channel migration near the project site because the channel is in a forested area, making it difficult to decipher where the channel is in each aerial photo.

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The channel was observed to be unconfined upstream, and on the border of unconfined downstream. The floodplains are highly accessible to flow at the 100-year and 500-year events. However, no signs of erosion or lateral migration were observed in the field, and hardpan material was common throughout the upstream and downstream reaches. As a result, the risk for lateral migration at this site is anticipated to be low.

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8.2 Long-term Aggradation/Degradation of the Riverbed

The proposed stream grading very closely matches the existing upstream and downstream gradients. Additionally, the longitudinal profile presented in Section 2.8.4 indicates that the slopes for 1,500 feet upstream and 500 feet downstream are similar and generally lay along a consistent average grade. These factors in combination with site observations lead to a conclusion that anticipated long-term aggradation and degradation will be minimal at this site.

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8.3 Local Scour

Three types of scour will be evaluated at this site: bend scour upstream near the inlet, inlet scour, and contraction scour. Initial scoping level calculations indicate the amount of local scour will likely be small, on the order of 1 feet. These forms of scour will be evaluated in greater depth after the stream channel design has been finalized.

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Because the stream was observed to go dry during the summer of 2021, large wood pieces placed in the channel will not have preformed scour holes constructed prior to rootwad placement.

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Summary

Table 18 presents a summary of the PHD development parameters and specifications.

Table 18: Report summary

Stream crossing category	Elements	Values	Report location
Habitat gain	Total length	NA	Not reported by WDFW
Bankfull width	Average BFW	18.0'	2.8.2 Channel Geometry
	Reference reach found?	Y	2.8.1 Reference Reach Selection
Channel slope/gradient	Existing crossing	0.1%	2.8.4 Vertical Channel Stability
	Reference reach	0.7%	2.8.2 Channel Geometry
	Proposed	0.7%	4.4.2 Channel Planform and Shape
Countersink	Proposed	FHD	4.7.3 Freeboard
	Added for climate resilience	FHD	4.7.3 Freeboard
Scour	Analysis	FHD	8 Scour Analysis
	Streambank protection/stabilization	FHD	8 Scour Analysis
Channel geometry	Existing	Perpendicular	2.8.2 Channel Geometry
	Proposed	Skewed	4.4.2 Channel Planform and Shape
Floodplain continuity	FEMA mapped floodplain	N	6 Floodplain Changes
	Lateral migration	N	2.8.5 Channel Migration
	Floodplain changes?	Y	6 Floodplain Changes
Freeboard	Proposed	3'	4.7.3 Freeboard
	Added for climate resilience	Y	4.7.3 Freeboard
	Additional recommended	0.0'	4.7.3 Freeboard
Maintenance clearance	Proposed	6'	4.7.3 Freeboard
Substrate	Existing	D_{50}=0.5”	2.8.3 Sediment
	Proposed	D_{50}=0.5”/0.8”	5.1 Bed Material
Hydraulic opening	Proposed	25'	4.7.2 Minimum Hydraulic Opening Width and Length
	Added for climate resilience	N	4.7.2 Minimum Hydraulic Opening Width and Length
Channel complexity	LWM	Y	5.2 Channel Complexity
	Meander bars	Y	4.4.2 Channel Planform and Shape

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	Boulder clusters	MAYBE	4.4.2 Channel Planform and Shape
	Mobile wood	N	5.2 Channel Complexity
Crossing length	Existing	97'	2.7.2 Existing Conditions
	Proposed	80'	4.7.2 Minimum Hydraulic Opening Width and Length
Floodplain utilization ratio	Flood-prone width	86.8	4.2 Existing–Conditions Model Results
	Average FUR upstream and downstream	5.1 4.7	4.2 Existing–Conditions Model Results
Hydrology/design flows	Existing	Regress	3 Hydrology and Peak Flow Estimates
	Climate resilience	Yes	3 Hydrology and Peak Flow Estimates
Channel morphology	Existing	Stage 1	2.8.2 Channel Geometry
	Proposed	Stage 1	5.2 Channel Complexity
Channel degradation	Potential?	N	8.2 Long-term Aggradation/Degradation of the Riverbed
	Allowed?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed
Structure type	Recommendation	N	4.7.1 Structure Type
	Type	NA	4.7.1 Structure Type

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References

Aquaveo. (2018). SMS Version 13.1.11.

Arcement, G.J. and V.R. Schneider, 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains, U.S. Geological Service Water-Supply Paper 2339.

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Barnard, R.J., J. Johnson, P. Brooks, K.M. Bates, B. Heiner, J.P. Klavas, D.C. Ponder, P.D. Smith, and P.D. Powers. 2013. *Water Crossing Design Guidelines*. Washington State Department of Fish and Wildlife. Olympia, Washington.

Barnes, H.H, 1967, Roughness characteristics of natural channels, U.S. Geological Service Water-Supply Paper 1849.

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Cluer, B., and C. Thorne. 2014. A stream evolution model integrating habitat and ecosystem benefits: sem incorporating habitat and ecosystem benefits. River Research and Applications, 30(2), 135–154. doi:10.1002/rra.2631.

DeVries, P. 2002. Bedload layer thickness and disturbance depth in gravel bed streams. Journal of Hydraulic Engineering, 128(11), pp.983-991.

DeVries, P., C. Huang, and R. Aldrich. 2014. Sediment Transport Modeling Along the Gravel-Sand Transition Zone of the Snohomish River, WA. In AGU Fall Meeting Abstracts (Vol. 2014, pp. EP53C-3675).

Fox, M. and S. Bolton. 2007. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forests Basins of Washington Stat. North American Journal of Fisheries Management. Vol 27, Issue 1. Pg. 342–359.

Lisle, T.E., J.M. Nelson, J. Pitlick, M.A. Madej, and B.L. Barkett. 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research, 36(12), pp.3743-3755.

Logan, R.L. 2003. Geologic Map of the Shelton 1:100,000 Quadrangle, Washington. Washington State Department of Natural Resources.

Mastin, M.C., C.P. Konrad, A.G, Veilleux, and A.E. Tecca. 2016. Magnitude, frequency, and trends of floods at gaged and ungaged sites in Washington, based on data through water year 2014 (ver 1.2, November 2017): U.S. Geological Survey Scientific Investigations Report 2016–5118, 70 p., http://dx.doi.org/10.3133/sir20165118.

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Mooney, D.M., C.L. Holmquist-Johnson, and S. Broderick. 2007. Rock ramp design guidelines. Bureau of Reclamation.

NLCD (National Land Cover Database). 2016. https://www.mrlc.gov/data/nlcd-2016-land-cover-conus Accessed June 2020.

NRCS (Natural Resources Conservation Service), United States Department of Agriculture. 2020. Web Soil Survey. Available online at the following link: http://websoilsurvey.sc.egov.usda.gov/. Accessed May 2020.

Pasternack, G.B., A.T. Gilbert, J.M. Wheaton, and E.M. Buckland. 2006. Error propagation for velocity and shear stress prediction using 2D models for environmental management. Journal of Hydrology, 328(1-2), pp.227-241.

Pasternack, G.B. and R.A. Brown. 2013. Ecohydraulic design of riffle-pool relief and morphological unit geometry in support of regulated gravel-bed river rehabilitation. DOI 10.1002/9781118526576.ch20.

PRISM Climate Group. 2019. Oregon State University, http://prism.oregonstate.edu, created February 4, 2004.

Rapp, C., and Abbe, T. B. (2003). A Framework for Delineating Channel Migration Zones (#03-06-027). Ecology Publication. Washington State Department of Transportation and Washington State Department of Ecology.

Richards, K. 1982. Rivers: Form and process in alluvial channels. Methuen & Co. New York NY. 358p.

Rieman, B.E., and J.D. McIntyre. 1993. *Demographic and habitat requirements for conservation of bull trout.* USDA Forest Service, Intermountain Research Station. General Technical Report INT-302.

Robinson, D., A., Zundel, C. Kramer, R. Nelson, W. deRosset, J. Hunt, S. Hogan, and Y. Lai. 2019. Two-dimensional hydraulic modeling for highways in the river environment – Reference document. Federal Highway Administration Publication No. FHWA-HIF-19-061. October.

Salo, E.O. 1991. Life history of Chum salmon (Oncorhynchus keta). Pages 231–309 in C. Groot and L. Margolis, eds. Pacific Salmon Life Histories. UBC Press, University of British Columbia, Vancouver, British Columbia.

Schumm, S.A., M.D. Harvey & C.C. Watson. 1984. Incised channels: morphology, dynamics and control. Water Resources Publications, Littleton, Colorado.

StreamNet. 2020. Pacific Northwest salmonid and critical habitat distribution. StreamNet, Portland, Oregon. http://www.streamnet.org/. Accessed May 2020.

SWIFD (Statewide Washington Integrated Fish Distribution) online. 2020. WSDOT

USACE (U.S. Army Corps of Engineers). 1994. Hydraulic design of flood control channels. EM-1110-2-1601.

USBR (United States Department of the Interior, Bureau of Reclamation). 2017. SRH-2D Version 3.2.4.

USFS (United States Department of Agriculture, Forest Service). 2008. Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings, Appendix E.

USGS (United States Geological Survey). 2016. The StreamStats program, online at http://streamstats.usgs.gov, accessed on June 27, 2019.

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USGS and Quantum Spatial. 2019. Olympic Peninsula, Washington 3DEP LiDAR- Area 1 Technical Data Report.

USGS (United States Geological Survey) and Quantum Spatial. 2019, Olympic Peninsula, Washington 3DEP LiDAR- Area 1 Technical Data Report.

WDFW (Washington Department of Fish and Wildlife). 2018. Habitat Assessment Data for UNT to Big Creek (WDFW ID 990033) at U.S. 101 MP 102.97. Unpublished.

WDFW (Washington Department of Fish and Wildlife). 2020a. SalmonScape. http://wdfw.wa.gov/mapping/salmonscape. Accessed May 2020.

WDFW (Washington Department of Fish and Wildlife). 2020b. Priority Habitats and Species map. Accessed May 2020.

WDFW (Washington Department of Fish and Wildlife). 2021 Fish Passage and Diversion Screening Inventory Database Site Description Report, Accessed June 2021.

WDNR (Washington State Department of Natural Resources), 2016, Surface geology, 1:100,000--GIS data, November: Washington Division of Geology and Earth Resources Digital Data Series DS-18, version 3.1, previously released June 2010 http://www.dnr.wa.gov/publications/ger_portal_surface_geology_100k.zip (accessed via the Geologic Information Portal, Aug 2021)

WDNR (Washington State Department of Natural Resources), 2020a, Landslide protocol inventory mapping--GIS data, February: Washington Geological Survey Digital Data Series 19, version 2.0, previously released January, 2019. https://fortress.wa.gov/dnr/geologydata/publications/data_download/ger_portal_landslide_inventory.zip (accessed via the Geologic Information Portal, Aug 2021)

WDNR (Washington State Department of Natural Resources), 2020b, Landslide Compilation--GIS data, February: Washington Geological Survey Digital Data Series 12, version 5.2, previously released January, 2019. https://fortress.wa.gov/dnr/geologydata/publications/data_download/ger_portal_landslide_compilation.zip. (accessed via the Geologic Information Portal, Aug 2021)

WSDOT (Washington State Department of Transportation). 2011. Climate impacts vulnerability assessment. Available: https://www.wsdot.wa.gov/sites/default/files/2017/11/15/ENV-Climate-VulnerabilityAssessment.pdf

WSDOT (Washington State Department of Transportation). 2019. Hydraulics Manual. Olympia, Washington. Publication M 23-03.06.

Wilcock, P.R., 1996. Estimating local bed shear stress from velocity observations. Water Resources Research, 32(11), pp.3361-3366.

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Wilcock, P.R., Barta, A.F., Shea, C.C., Kondolf, G.M., Matthews, W.G. and Pitlick, J., 1996. Observations of flow and sediment entrainment on a large gravel-bed river. Water Resources Research, 32(9), pp.2897-2909.

Appendices

Appendix A: FEMA Floodplain Map

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations (to be completed at FHD)

Appendix G: Manning's Calculations

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Co-Manager Comments on Draft PHD Report and Stream Team Responses

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This appendix was not used because it is used for the FHD Report, not the PHD Report.

Appendix G: Manning's Calculations

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

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